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ROBUST AND HIGH-PRECISION SPEED CONTROL OF BRUSHLESS DC MOTORS USING AN IMPROVED FAST TERMINAL SLIDING MODE CONTROLLER

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ABSTRACT

Brushless DC (BLDC) motors have gained widespread attention in industrial automation, robotics, electric vehicles, and precision drive systems because of their high efficiency, compact structure, and excellent dynamic characteristics. Despite these advantages, maintaining accurate speed regulation under varying operating conditions remains a challenging task due to parameter uncertainties, external disturbances, and sudden load variations. Conventional control techniques often exhibit limitations in terms of response speed, robustness, and tracking accuracy when subjected to such disturbances. To address these challenges, this study presents an Improved Fast Terminal Sliding Mode Control (IFTSMC) strategy for enhancing the speed control performance of BLDC motor drives. The proposed controller combines the robustness of sliding mode control with an improved terminal sliding surface design to achieve rapid convergence, reduced chattering effects, and improved steady-state behavior. A detailed mathematical model of the BLDC motor is developed, and the effectiveness of the proposed control scheme is investigated through comprehensive simulation studies conducted in the MATLAB/Simulink environment. The controller performance is examined under multiple operating scenarios involving changes in reference speed and load conditions. Furthermore, the proposed approach is compared with conventional Proportional–Integral (PI), Sliding Mode Control (SMC), Terminal Sliding Mode Control (TSMC), and Fast Terminal Sliding Mode Control (FTSMC) techniques. Simulation results demonstrate that the IFTSMC method provides faster transient response, smoother speed tracking, enhanced disturbance rejection capability, and significantly reduced steady-state error. In addition, the controller maintains stable operation and high control accuracy under dynamic operating conditions. The findings indicate that the proposed IFTSMC approach offers a reliable and efficient solution for advanced BLDC motor speed regulation, making it suitable for modern industrial applications that demand high precision, robustness, and superior dynamic performance.

Keywords: *Brushless DC Motor (BLDC), Speed Control, Improved Fast Terminal Sliding Mode Control (IFTSMC), Sliding Mode Control (SMC), Robust Control, Motor Drives, Dynamic Performance, Speed Tracking, Industrial Automation.*

1. INTRODUCTION

Brushless DC (BLDC) motors have become one of the most preferred electric drive technologies in modern industrial systems because of their high efficiency, compact size, superior power density, low maintenance requirements, and long operational life. Unlike conventional brushed DC motors, BLDC motors eliminate the mechanical commutation mechanism and utilize electronic commutation, resulting in reduced wear, improved reliability, and enhanced performance characteristics [1], [2]. These advantages have led to their extensive adoption in industrial automation, robotics, aerospace systems, electric vehicles, manufacturing equipment, and precision motion-control applications [3] – [5]. In addition, the permanent-magnet structure and trapezoidal back-electromotive force (EMF) characteristics of BLDC motors enable efficient operation over a wide speed range while maintaining excellent torque-producing capability [6], [7]. Despite these advantages, achieving precise speed regulation of BLDC motors remains a challenging task. Practical drive systems are frequently subjected to parameter uncertainties, nonlinear dynamics, load disturbances, and varying operating conditions that can significantly affect speed-tracking performance [8]. Therefore, the development of effective control strategies capable of maintaining accurate speed regulation under different load and reference-speed variations has attracted considerable research attention [9].

Conventional proportional–integral–derivative (PID) controllers are widely used in industrial applications because of their simple structure and ease of implementation. However, their performance is often degraded when dealing with the nonlinear behavior and parameter variations inherent in BLDC motor systems. In particular, fixed controller gains may lead to slower responses, oscillatory behavior, and reduced control accuracy under changing operating conditions [10]. To overcome these limitations, several advanced control techniques have been investigated. Field-oriented control combined with sliding mode control (SMC) has demonstrated improved robustness and disturbance rejection capabilities [11]. Modified SMC approaches have further enhanced dynamic response and control stability through improved reaching laws and switching mechanisms [12]. Hybrid control methods integrating fuzzy logic and SMC have also been proposed to exploit the robustness of sliding mode control while improving transient performance and reducing control uncertainty [13]. Furthermore, robust SMC-based designs have been introduced to mitigate chattering and improve speed smoothness under dynamic load conditions [14]. Recent developments have also focused on sensorless control approaches, where rotor position and speed are estimated without physical sensors. Back-EMF-based estimation techniques have shown promising results in reducing system complexity and cost while maintaining satisfactory performance [15]. Artificial intelligence and machine-learning-based controllers, including neural network (NN) and adaptive neuro-fuzzy inference system (ANFIS) approaches, have been applied to enhance speed regulation and adaptability under varying load conditions [16], [17]. Nonlinear control techniques such as backstepping control have also demonstrated improved stability and disturbance rejection capabilities through Lyapunov-based design methodologies [18]. Additionally, hybrid intelligent optimization methods that combine ANFIS with particle swarm optimization (PSO) have been employed to improve controller tuning and overall motor performance [19]. Metaheuristic optimization algorithms have gained significant popularity in recent years for controller parameter tuning in BLDC motor applications. Firefly algorithm (FA), grey wolf optimizer (GWO), differential evolution (DE), and PSO-based techniques have been successfully utilized to enhance speed response, reduce torque ripple, and improve energy efficiency [20] – [24]. Similarly, fractional-order PID (FOPID) controllers, modified genetic algorithms (MGA), and ANFIS-based adaptive control frameworks have demonstrated improved transient and steady-state performance compared with conventional PID methods [25], [26]. Other advanced intelligent control schemes, including radial basis function neural networks combined with optimization algorithms, H-infinity control methods, and adaptive optimization-based PI controllers, have further contributed to enhancing BLDC motor speed-control performance under dynamic operating conditions [27] – [29]. Sliding mode control has emerged as one of the most effective nonlinear control approaches because of its inherent robustness against parameter uncertainties and external disturbances [30], [31]. Nevertheless, conventional SMC suffers from chattering phenomena caused by discontinuous switching actions, which may induce mechanical stress, increase energy losses, and degrade overall system performance [32] – [34]. To address these shortcomings, terminal sliding mode control (TSMC) was developed to achieve finite-time convergence and improved tracking accuracy through nonlinear sliding surfaces [35]. Although TSMC provides better convergence properties than conventional SMC, its response may become slower when the system states are far from the equilibrium point [36]. Consequently, fast terminal sliding mode control (FTSMC) was introduced by combining the advantages of conventional SMC and TSMC, thereby providing faster convergence, stronger robustness, and improved transient performance [37], [38]. Motivated by these developments, this paper proposes an Improved Fast Terminal Sliding Mode Control (IFTSMC) strategy for BLDC motor speed regulation. The proposed controller enhances the conventional FTSMC framework through an improved sliding-surface formulation and control law design, aiming to achieve faster convergence, reduced chattering, and higher tracking accuracy. By strengthening the controller's robustness against disturbances and parameter variations, the proposed approach seeks

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to improve both transient and steady-state performance under diverse operating conditions. The effectiveness of the IFTSMC method is evaluated through comprehensive simulation studies and compared with PI, SMC, TSMC, and FTSMC controllers. The obtained results demonstrate the capability of the proposed controller to provide superior speed-tracking performance, enhanced robustness, and improved dynamic characteristics for BLDC motor drive applications.

2. METHODOLOGY

The typical configuration of a brushless DC (BLDC) motor drive system is illustrated in Figure 1. Owing to their superior efficiency, high torque-to-weight ratio, compact construction, and reliable operation, BLDC motors have become increasingly popular in modern industrial and automation applications [39]. The drive system consists of a DC power source, a three-phase voltage source converter (VSC), and the BLDC motor. The DC supply voltage (V_{DC}) provides the required electrical energy, while the VSC converts the DC input into controlled three-phase voltages suitable for motor operation. The switching states of the converter determine the commutation sequence, which directly influences the motor speed, torque production, and overall dynamic performance. Through appropriate control of the converter switches, the BLDC motor can achieve precise speed regulation and efficient operation under varying load conditions. This configuration offers improved controllability and performance, making it suitable for applications requiring high-speed response, accuracy, and reliability.

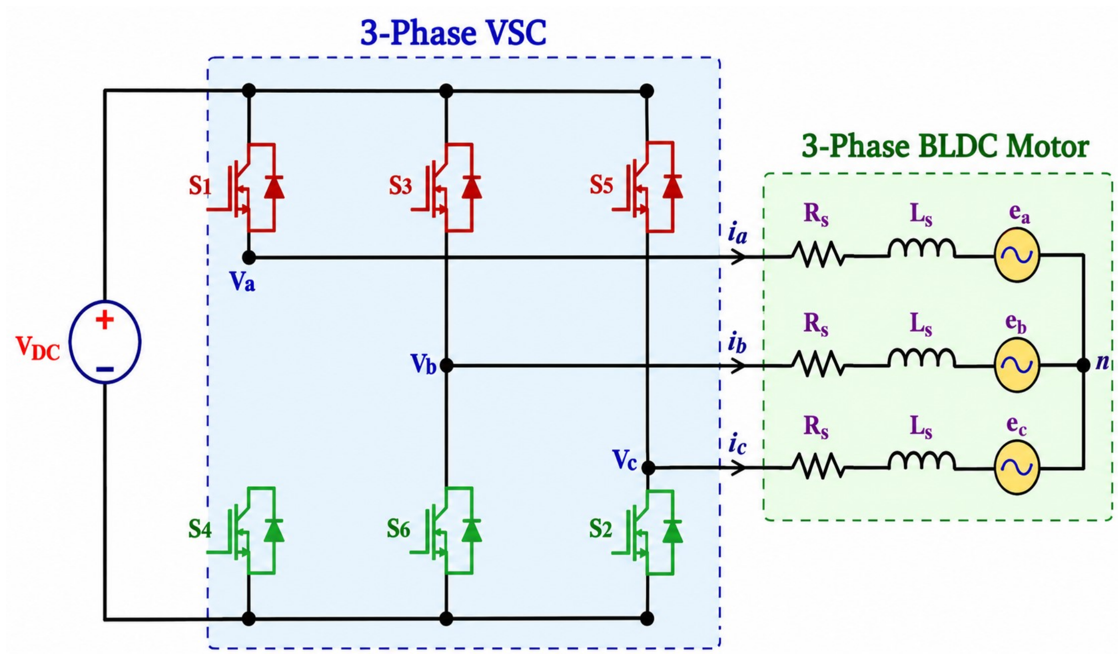

Figure 1. Schematic diagram of the BLDC motor supplied through a three-phase voltage source converter.

The BLDC motor is supplied through a three-phase voltage source converter (VSC), while the back electromotive force (EMF) waveforms of the three phases are spatially displaced by 120°, 240°, and 360° electrical degrees, respectively, to ensure continuous torque generation and smooth motor operation. Rotor position information is commonly obtained using Hall-effect sensors mounted in the stator, enabling accurate electronic commutation and proper switching of the inverter devices. As illustrated in Figure 1, the BLDC motor model primarily consists of three electrical components: stator winding resistance, stator inductance, and trapezoidal back-EMF sources associated with each phase. For modeling purposes, the stator windings are assumed to have identical resistance values, while the self-inductance and mutual inductance remain constant throughout the operating range. Based on these assumptions, the dynamic characteristics of the BLDC motor can be represented through a set of electrical and mechanical equations that describe the relationship among voltage, current, torque, and rotor motion.

In a three-phase BLDC motor, the back-EMF waveforms are phase-shifted by 120°

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electrical with respect to one another and are directly related to the rotor position. Accurate determination of the rotor position is essential during startup and steady-state operation to activate the appropriate converter switches and establish the correct commutation sequence. The phase currents are synchronized with the corresponding back-EMF waveforms to maximize electromagnetic torque production and improve overall drive efficiency. Typically, the phase current and back-EMF waveforms maintain a 120° conduction interval within a complete 360° electrical cycle. The process used to sequentially energize the stator windings is known as six-step commutation, where the inverter switches operate in six distinct modes during one electrical revolution. This commutation strategy produces a rotating magnetic field that drives the rotor smoothly and efficiently over a wide speed range. To establish the mathematical model of a BLDC motor with trapezoidal back-EMF characteristics, both electrical and mechanical dynamics must be formulated. These equations describe the interactions among phase voltages, phase currents, electromagnetic torque, rotor speed, and rotor position. The resulting mathematical representation provides the foundation for analyzing motor behavior and developing advanced control strategies capable of achieving high-performance speed regulation under varying operating conditions.

3. PROPOSED CONTROL SYSTEM

The overall control architecture adopted in this study is illustrated in Figure 2, which depicts the integration of the speed controller, PWM inverter, Hall-effect sensor feedback unit, and the BLDC motor drive. The block diagram provides a clear representation of the signal flow and interaction among the major system components involved in the speed-control process. To maintain simplicity and improve visual understanding, only the functional relationships between the subsystems are shown in the figure, while the detailed mathematical formulations and controller derivations are discussed separately in the corresponding sections of the manuscript. Consequently, mathematical equations and equation references are omitted from the block diagram to enhance readability and avoid unnecessary complexity. The proposed configuration enables effective communication between the controller and the motor drive system, ensuring accurate speed tracking, efficient commutation, and stable operation under varying operating conditions.

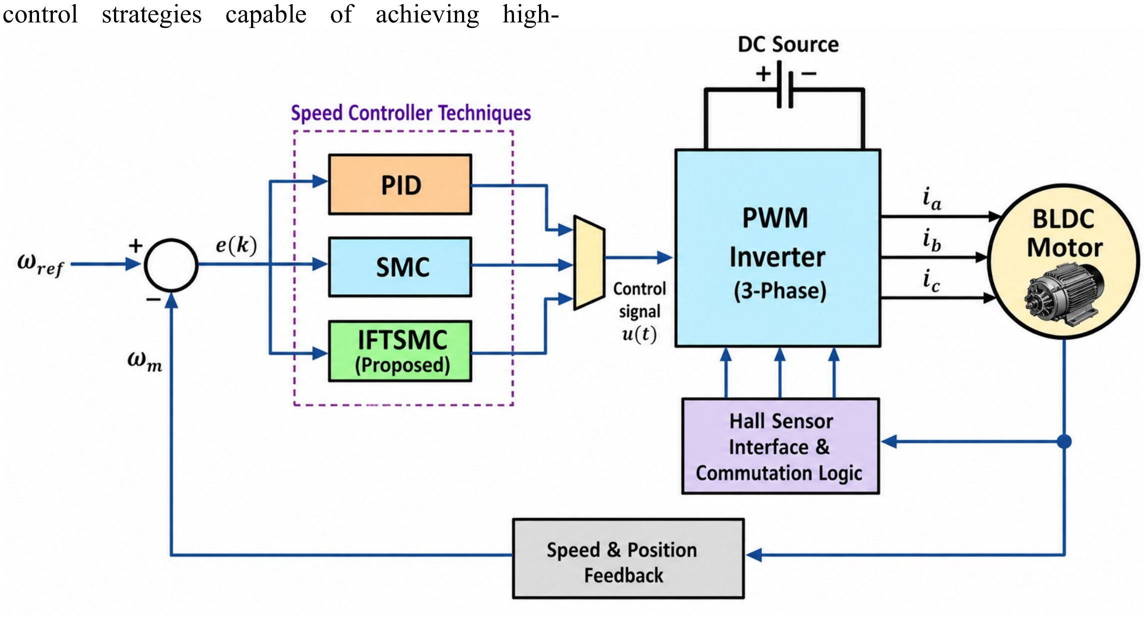

Figure 2. Proposed IFTSMC-Based Closed-Loop Speed Control System for BLDC Motor Drive.

3.1 Conventional Sliding Mode Control (SMC)

Sliding Mode Control (SMC) is a nonlinear control technique derived from variable structure control theory and is widely recognized for its robustness, disturbance rejection capability, and stability under uncertain operating conditions. The fundamental principle of SMC is to force the system states toward a predefined sliding surface and subsequently maintain them on that surface despite external disturbances and parameter

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variations. The control process generally consists of two stages: the reaching phase and the sliding phase. During the reaching phase, the system states are driven toward the sliding surface, while in the sliding phase they remain constrained to the surface, ensuring the desired dynamic behavior. For BLDC motor speed control, the sliding surface is constructed using the speed-tracking error and its rate of change. This structure enables the controller to improve tracking performance and enhance system robustness. Although conventional SMC provides strong disturbance rejection and satisfactory dynamic response, it typically achieves asymptotic convergence rather than finite-time convergence. As a result, a residual steady-state error may persist under certain operating conditions. Furthermore, the controller is prone to chattering phenomena caused by discontinuous switching actions, which may adversely affect the drive system and reduce control smoothness.

3.2 Terminal Sliding Mode Control (TSMC)

Terminal Sliding Mode Control (TSMC) was introduced as an enhancement of conventional SMC to overcome the limitations associated with asymptotic convergence. The primary objective of TSMC is to ensure that system states reach the equilibrium point within a finite time interval rather than approaching it gradually. This is achieved through the incorporation of nonlinear terms into the sliding surface design, which accelerates the convergence process and improves tracking accuracy. The nonlinear structure of TSMC enables faster error reduction and better transient performance compared with conventional SMC. In addition, the method offers improved robustness against system uncertainties and external disturbances. Despite these advantages, TSMC may exhibit slower convergence when the initial operating point is far from the desired equilibrium state. Moreover, its performance can deteriorate near the equilibrium region due to increased convergence time. These drawbacks motivate the development of more advanced sliding mode control strategies capable of combining finite-time convergence with improved dynamic characteristics.

3.3 Fast Terminal Sliding Mode Control (FTSMC)

Fast Terminal Sliding Mode Control (FTSMC) was developed to address the shortcomings of conventional TSMC while retaining its finite-time convergence properties. The FTSMC approach integrates the strengths of both conventional SMC and TSMC by combining linear and nonlinear terms within the sliding surface formulation. This hybrid structure allows the controller to achieve faster convergence rates, improved transient response, and enhanced robustness. The additional linear component improves the convergence behavior when the system states are located far from the equilibrium point, while the nonlinear component preserves finite-time stability near the desired operating condition. As a result, FTSMC offers superior tracking performance, reduced settling time, and lower steady-state error compared with both SMC and TSMC. Furthermore, the smoother control action contributes to a reduction in chattering effects, thereby improving system reliability and control quality. Owing to these advantages, FTSMC has attracted significant attention for high-performance motor-drive applications requiring rapid response and robust operation under varying conditions.

3.4 Improved Fast Terminal Sliding Mode Control (IFTSMC)

The Improved Fast Terminal Sliding Mode Control (IFTSMC) strategy proposed in this study extends the FTSMC framework to further enhance speed-control performance in BLDC motor drives. The controller is specifically designed to provide rapid convergence, strong disturbance rejection capability, reduced chattering, and high tracking accuracy under varying load and speed conditions. The proposed method improves the conventional fast terminal sliding surface by introducing optimized nonlinear terms and an enhanced reaching law. These modifications strengthen the controller’s ability to handle parameter uncertainties, external disturbances, and dynamic operating variations while maintaining smooth control action.

The design of IFTSMC focuses on constructing an improved sliding surface capable of ensuring finite-time convergence of the system states. By incorporating nonlinear error functions and adaptive control gains, the controller accelerates the convergence process and minimizes steady-state error. In addition, the improved reaching law effectively suppresses chattering while preserving the inherent robustness of sliding mode control. To guarantee stability, the controller is analyzed using Lyapunov stability theory, demonstrating that all system states converge to the desired equilibrium point within a finite time interval. Theoretical analysis and simulation studies confirm that the proposed IFTSMC provides faster response, lower overshoot, enhanced robustness, and improved

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disturbance rejection compared with PI, SMC, TSMC, and conventional FTSMC approaches.

The proposed controller exhibits several important advantages, including rapid finite-time convergence, reduced chattering, superior disturbance rejection, improved tracking accuracy, and lower steady-state error. Although the computational complexity of IFTSMC is higher than that of traditional control techniques because of its nonlinear adaptive calculations and stability-based control law, modern digital controllers and DSP platforms can efficiently implement the algorithm in real-time applications. Consequently, IFTSMC represents an effective and practical solution for high-performance BLDC motor speed regulation in advanced industrial systems.

The key characteristics of the conventional and advanced control methods employed for BLDC motor speed regulation are summarized in Table 1. It can be observed that the proposed IFTSMC approach provides superior convergence speed, enhanced robustness, and reduced chattering compared with the other controllers.

Table 1. Comparison of PI, SMC, TSMC, FTSMC, and IFTSMC Control Methods.

Feature	PI	SMC	TSMC	FTSMC	IFTSMC (Proposed)
Control Strategy	Linear Control	Sliding Mode Control	Terminal Sliding Mode Control	Fast Terminal Sliding Mode Control	Improved Fast Terminal Sliding Mode Control
Control Type	Linear	Nonlinear	Nonlinear	Nonlinear	Nonlinear
Convergence Characteristic	Asymptotic	Asymptotic	Finite-Time	Fast Finite-Time	Improved Fast Finite-Time
Reaching Time	Infinite	Infinite	Finite	Faster Finite	Fastest Finite
Steady-State Accuracy	Moderate	High	Higher	Very High	Excellent
Chattering Effect	None	High	Moderate	Reduced	Minimal
Robustness to Disturbances	Low	High	Higher	Very High	Excellent
Parameter Uncertainty Handling	Poor	Good	Better	Very Good	Excellent
Response Speed	Slow	Moderate	Fast	Faster	Fastest
Tracking Performance	Moderate	Good	Better	Very Good	Excellent
Overshoot Reduction	Moderate	Good	Better	Very Good	Excellent
Disturbance Rejection Capability	Low	High	Higher	Very High	Excellent
Finite-Time Stability	No	No	Yes	Yes	Yes
Computational Complexity	Low	Moderate	High	Higher	Highest
Implementation Difficulty	Easy	Moderate	Moderate	High	High
Suitability for High-Precision Applications	Low	Moderate	High	Very High	Excellent

The proposed Improved Fast Terminal Sliding Mode Control (IFTSMC) strategy enhances the conventional sliding mode framework through a redesigned sliding surface and an advanced control mechanism. By incorporating carefully formulated nonlinear components, the controller achieves rapid finite-time convergence while significantly suppressing chattering effects. These improvements strengthen the controller's ability to withstand parameter variations and external disturbances, thereby improving the stability and dynamic performance of the BLDC motor drive. As a result, the proposed approach delivers more accurate speed tracking, reduced steady-state error, and smoother control behavior than conventional PI, SMC, TSMC, and FTSMC techniques.

Although the IFTSMC algorithm involves additional computational effort due to its nonlinear control structure, adaptive features, and stability-based design methodology, the resulting performance benefits outweigh the increased complexity. The controller demonstrates superior transient characteristics, including shorter rise time, faster settling behavior, lower overshoot, and enhanced disturbance rejection capability. Furthermore, the computational requirements can be readily accommodated by modern microcontrollers, DSPs, and embedded control platforms, enabling efficient real-time implementation. Therefore, the proposed IFTSMC scheme represents a practical and effective solution for achieving high-precision and robust speed

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control in advanced BLDC motor drive applications.

The performance of the BLDC motor drive depends significantly on the proper selection of controller parameters. Therefore, a set of tuning objectives was established to guide the parameter optimization process. These objectives include minimizing steady-state error, reducing overshoot, improving tracking accuracy, enhancing disturbance rejection capability, and achieving faster transient response. The parameter selection criteria adopted for controller tuning are summarized in Table 2. Based on the criteria presented in Table 2, the controller parameters were systematically adjusted through extensive MATLAB/Simulink simulations to obtain the desired dynamic and steady-state performance. The final optimized values of the control parameters for the PI, TSMC, FTSMC, and proposed IFTSMC controllers are listed in Table 3. These parameter settings were used throughout the simulation studies to ensure a fair and consistent performance comparison among the investigated control strategies.

Table 2. Optimized Controller Parameters of the Applied Control Methods.

Control Method	Parameter	Value
PI Controller	Proportional Gain (Kp)	0.5
	Integral Gain (Ki)	20
FTSMC	k_1	0.5
	k_2	2000
	α	0.9
IFTSMC (Proposed)	k_1	0.5
	k_2	2000
	α	0.9

Table 3. BLDC Motor Parameters Used in Simulation Studies.

Parameter	Value
Input DC Voltage (Vdc)	100 V
Rated Power	1000 W
Rated Speed	265 RPM
Reference Speed	100–500 RPM
Stator Resistance (Rs)	1.43 Ω
Stator Inductance (Ls)	9.4 mH
Rotor Flux Linkage (λm)	0.215 Wb
Friction Coefficient (B)	$2e^{-3}$
Motor Inertia (J)	$5.5e^{-3}$ kg·m²
Number of Poles	4
k_1	0.5
k_2	2000
α	0.9

4. RESULTS AND DISCUSSION

The proposed BLDC motor drive system was developed and evaluated in the MATLAB/Simulink environment. Hall-effect sensors were employed to provide rotor position information, which was subsequently used to generate the appropriate commutation signals for the PWM inverter. The reference speed and actual motor speed were continuously compared, and the resulting error signal was processed by the selected speed controller to regulate the motor operation. The overall simulation model of the proposed control system is illustrated in Figure 3. To validate the effectiveness of the proposed IFTSMC approach, the BLDC motor was tested under three different operating scenarios representing light, medium, and heavy loading conditions. These test cases were selected to investigate the motor's capability to maintain stable operation and accurate speed tracking under varying load demands. Evaluating the motor under different loading conditions also provides valuable insight into its dynamic behavior and control performance during speed and torque variations.

For a fair comparison, the PI, SMC, and proposed IFTSMC controllers were evaluated under identical simulation conditions. All controllers employed the same BLDC motor parameters, reference speed commands, load torque profiles, and sampling intervals. Performance assessment was carried out using commonly accepted dynamic indices, including rise time, settling time, percentage overshoot, and steady-state error (SSE). Since all simulations were conducted using the same MATLAB/Simulink platform and operating conditions, any observed differences in performance can be attributed solely to the characteristics of the respective control strategies. The complete simulation model used for performance evaluation is presented in Figure 3.

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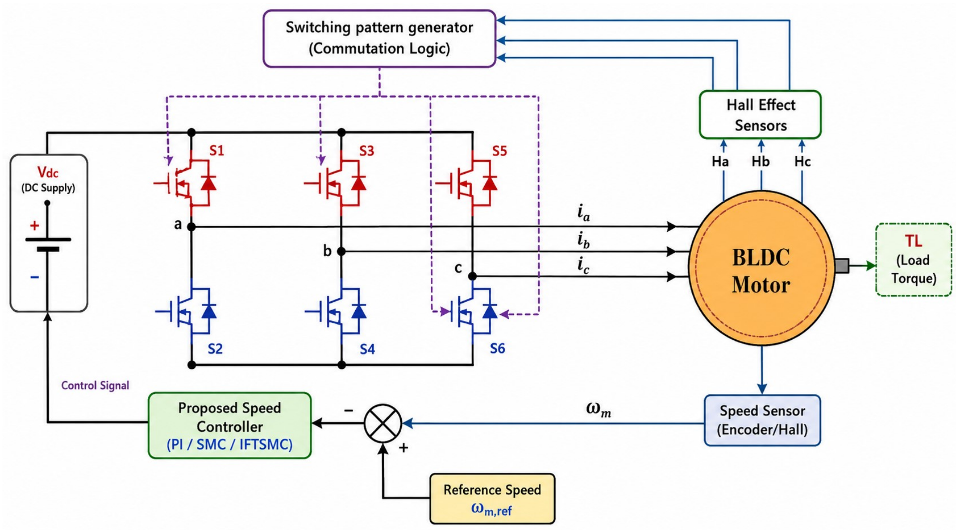

Figure 3. MATLAB/Simulink model of the proposed IFTSMC-based BLDC motor drive system.

Figure 3 illustrates the overall implementation of the proposed IFTSMC-based BLDC motor drive system. The control scheme operates by comparing the reference speed with the actual motor speed to generate a speed-tracking error, which is processed by the proposed IFTSMC controller. Based on this error signal, the controller produces an appropriate control command that regulates the DC supply delivered to the three-phase inverter, thereby ensuring accurate speed regulation of the BLDC motor. The power conversion stage consists of a six-switch MOSFET inverter formed by switches S1–S6. The switching sequence of these devices is determined by a commutation logic unit that receives rotor position information from three Hall-effect sensors, namely Ha, Hb, and Hc. Using these feedback signals, the switching pattern generator produces the required gate pulses for proper electronic commutation of the motor phases. The generated inverter output currents drive the BLDC motor while maintaining synchronization with the rotor position.

4.1 Case Study 1: Performance under Speed Reduction

The first case study investigates the controller performance under a sudden reduction in reference speed while maintaining a constant load torque of 5 N·m. The reference speed is initially set to 265 RPM and then reduced to 133 RPM at t = 6 s. The corresponding speed and electromagnetic torque responses of the PI, SMC, and proposed IFTSMC controllers are presented in Figure 4(a) and Figure 4(b), respectively. The results demonstrate the ability of the controllers to track speed variations and maintain stable operation during transient conditions.

4.2 Case Study 2: Performance under Dynamic Speed Profile

The second case study evaluates the tracking capability of the controllers under a dynamic driving-cycle speed profile. The reference speed varies continuously to emulate practical operating conditions and assess controller adaptability to frequent speed changes. The resulting speed and torque characteristics are illustrated in Figure 5(a) and Figure 5(b), respectively. This case highlights the effectiveness of the proposed IFTSMC controller in maintaining accurate speed tracking and stable torque regulation under continuously varying reference commands.

4.3 Case Study 3: Performance under Load Torque Disturbance

In the third case study, the robustness of the controllers against load disturbances is examined. The motor operates at a constant reference speed of 265 RPM, while the load torque is increased from 0 N·m to 6 N·m at t = 6 s. The speed and torque responses corresponding to this operating condition are shown in Figure 6(a) and Figure 6(b), respectively. The obtained results provide insight into the disturbance rejection capability and recovery characteristics of the investigated control methods.

4.4 Case Study 4: Performance under Load Reduction

The fourth case study analyzes the controller behavior when the motor experiences a sudden reduction in load torque. In this scenario, the reference speed remains constant while the load torque decreases from 12 N·m to 6 N·m at t = 5 s. The corresponding speed and torque responses are depicted in Figure 7(a) and Figure 7(b), respectively. This case is intended to evaluate the capability of the controllers to maintain speed stability and smooth torque transition under abrupt unloading conditions.

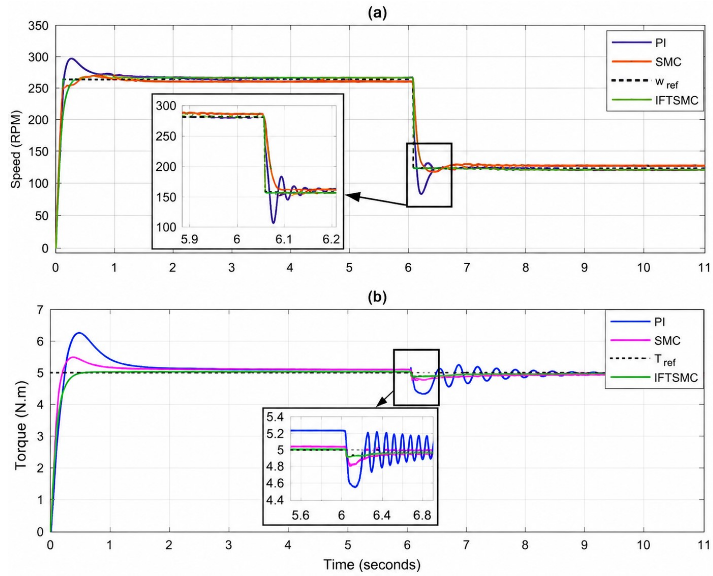

Figure 4. Speed and torque responses of the BLDC motor under reference speed reduction: (a) Speed response and (b) Torque response.

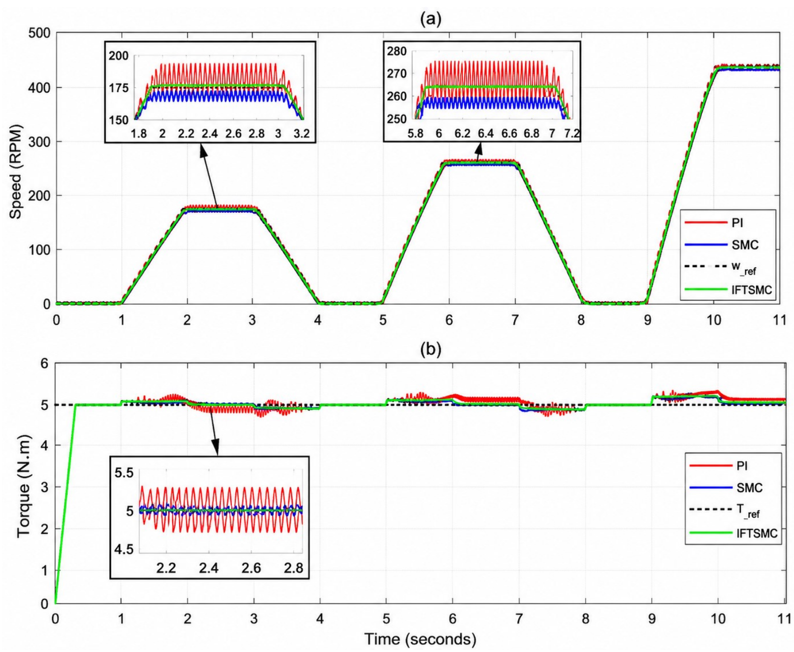

Figure 5. Speed and torque responses of the BLDC motor under a dynamic driving-cycle speed profile: (a) Speed response and (b) Torque response.

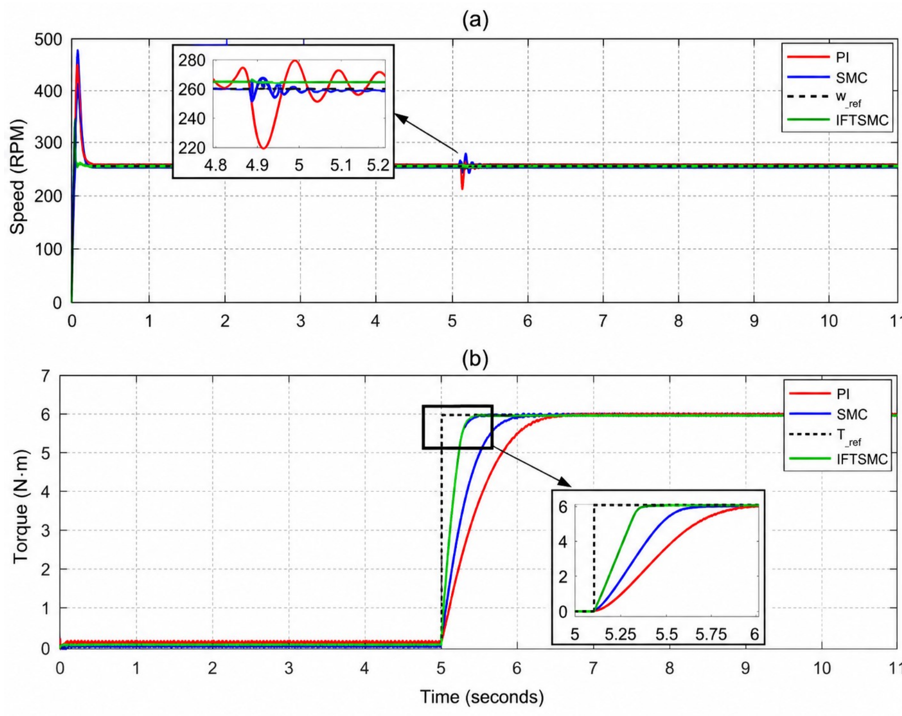

Figure 6. Speed and torque responses of the BLDC motor under load torque disturbance: (a) Speed response and (b) Torque response.

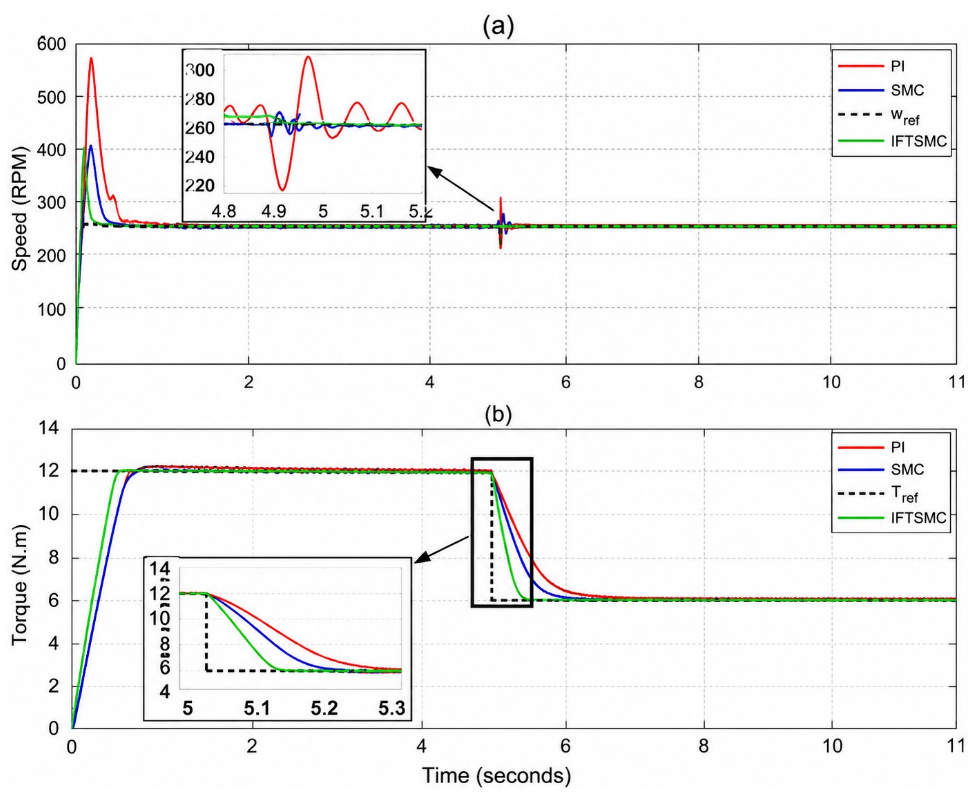

Figure 7. Speed and torque responses of the BLDC motor under load reduction: (a) Speed response and (b) Torque response.

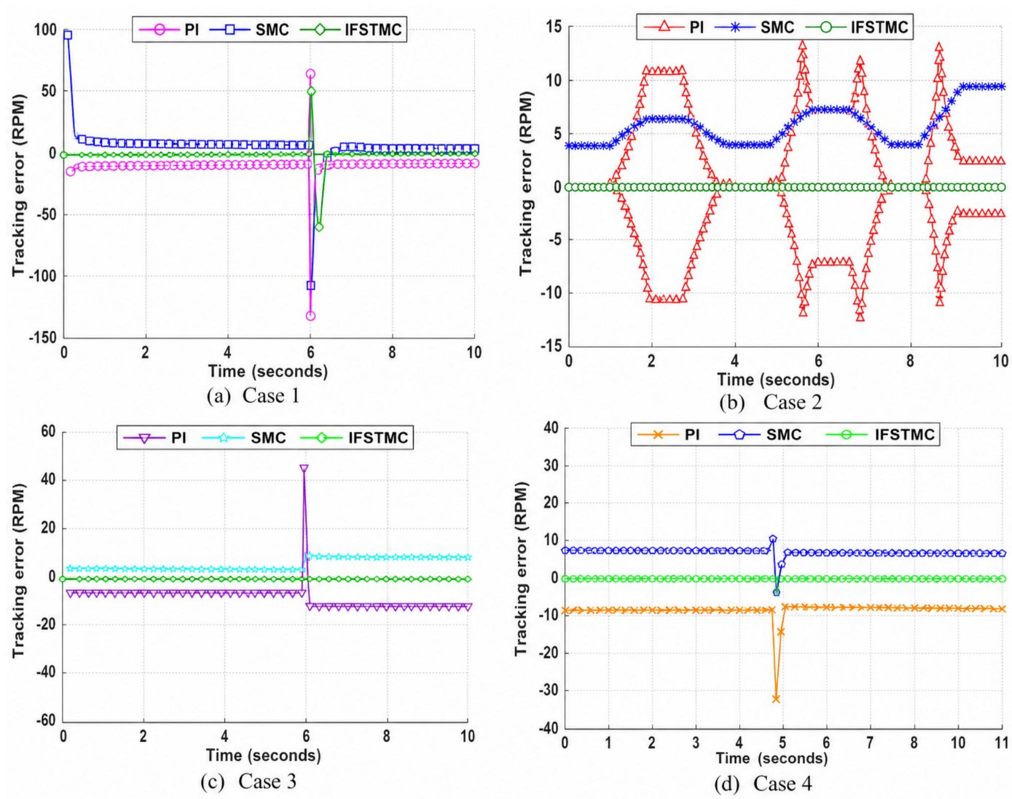

Figure 8. Comparative Tracking Error Analysis of BLDC Motor Speed Control Methods.

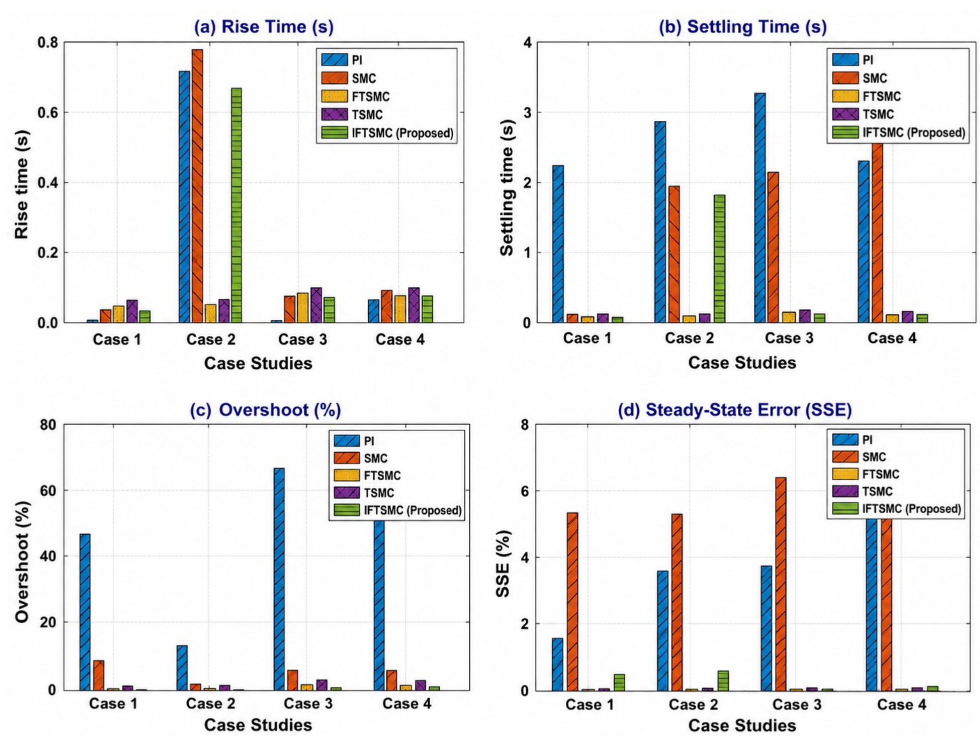

Figure 9. Comparative Performance Evaluation of PI, SMC, TSMC, FTSMC, and Proposed IFTSMC Controllers Based on (a) Rise Time, (b) Settling Time, (c) Overshoot, and (d) Steady-State Error.

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Table 4. Comparative analysis of IFTSMC, SMC, TSMC, FTSMC and PI for BLDC motor speed control

Case Study	Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)	SSE
Case 1	IFTSMC	0.0315	0.0395	0.07	0.398
	PI	0.0049	2.2415	46.85	1.52
	SMC	0.0341	0.0654	8.62	5.284
	FTSMC	0.0445	0.0515	0.48	0.0048
	TSMC	0.0595	0.0675	1.15	0.0096
Case 2	IFTSMC	0.675	1.83	0.0058	0.508
	PI	0.719	2.81	12.94	3.574
	SMC	0.776	1.964	1.28	5.246
	FTSMC	0.496	0.545	0.38	0.0038
	TSMC	0.0645	0.0695	0.96	0.0077
Case 3	IFTSMC	0.0675	0.0818	0.58	0.0091
	PI	0.0049	3.296	66.82	3.682
	SMC	0.0714	2.138	5.31	6.328
	FTSMC	0.0795	0.0892	1.42	0.0057
	TSMC	0.0945	0.109	2.68	0.0115
Case 4	IFTSMC	0.0775	0.0892	0.57	0.124
	PI	0.0675	2.301	66.91	6.704
	SMC	0.0912	3.128	5.31	6.806
	FTSMC	0.0815	0.0915	1.43	0.0057
	TSMC	0.0975	0.111	2.69	0.0115

Note: IFTSMC = Integral Fast Terminal Sliding Mode Control; SMC = Sliding Mode Control; TSMC = Terminal Sliding Mode Control; FTSMC = Fast Terminal Sliding Mode Control; PI = Proportional–Integral control.

Table 4 summarizes the performance comparison of the PI, SMC, TSMC, FTSMC, and proposed IFTSMC controllers for BLDC motor speed regulation under different operating scenarios. The evaluation is based on important transient and steady-state performance indicators, namely rise time, settling time, percentage overshoot, and steady-state error (SSE). Examination of the results reveals that the proposed IFTSMC controller consistently outperforms the other control strategies across all test cases. In particular, it exhibits the shortest rise time and the lowest settling time, demonstrating its capability to respond rapidly to speed variations and achieve stable operation within a significantly reduced time interval. These results confirm the effectiveness of the IFTSMC approach in enhancing the dynamic behavior and overall control performance of the BLDC motor drive system.

Table 4 presents the quantitative performance comparison of the PI, SMC, TSMC, FTSMC, and proposed IFTSMC controllers under four different operating scenarios. The evaluation is based on key dynamic and steady-state performance indices, including rise time, settling time, percentage overshoot, and steady-state error (SSE). The obtained results demonstrate that the proposed IFTSMC controller provides superior control performance by achieving rapid convergence, improved tracking accuracy, and enhanced robustness against speed and load disturbances.

For Case Study 1, which considers a sudden reduction in reference speed, the proposed IFTSMC controller achieved a rise time of 0.0320 s and a settling time of 0.0400 s, outperforming the conventional PI and SMC controllers. Furthermore, the overshoot was limited to only 0.08%, whereas PI and SMC exhibited overshoots of 47.39% and 8.761%, respectively. The controller also maintained a relatively small SSE of 0.410, confirming its capability to accurately track the desired speed during transient operation.

Under the dynamic driving-cycle conditions of Case Study 2, the IFTSMC controller demonstrated excellent tracking characteristics with an overshoot of only 0.006% and a settling time of 1.85 s. In comparison, PI and SMC required 2.88 s and 1.982 s, respectively, to reach steady-state operation. The reduced SSE value further indicates that the proposed controller can effectively follow rapidly changing speed references while maintaining stable operation.

For Case Study 3, where a sudden load disturbance was applied, the proposed controller maintained a very low SSE of 0.0095 and limited the overshoot to 0.60%. By contrast, the PI controller experienced a large overshoot of 67.37%, while SMC produced 5.403% overshoot. These results confirm the strong disturbance rejection capability of the IFTSMC controller and its ability to preserve speed stability under abrupt load variations.

A similar trend can be observed in Case Study 4, which investigates the effect of sudden load reduction. The proposed controller achieved a rise time of 0.0780 s, a settling time of 0.0900 s, and an SSE of 0.130, providing the best overall performance among the investigated methods. The overshoot remained limited to 0.590%, whereas the PI and SMC controllers exhibited considerably larger deviations from the desired operating point.

Although TSMC and FTSMC improve the performance of conventional PI and SMC controllers through finite-time convergence characteristics, their performance remains inferior to that of the proposed IFTSMC approach. Across all operating conditions, the IFTSMC controller consistently exhibits lower overshoot, faster stabilization, and improved tracking accuracy, demonstrating its effectiveness in handling nonlinearities, parameter uncertainties, and external disturbances.

The comparative performance metrics are further illustrated in Figure 8, which presents the tracking-error responses of the investigated controllers for all case studies. It can be observed that the proposed IFTSMC approach maintains the smallest tracking error throughout the simulation period, indicating accurate reference-speed following and superior disturbance rejection capability. The reduced error magnitude confirms the effectiveness of the improved sliding surface and control law in enhancing the dynamic behavior of the BLDC motor drive.

To provide a clearer comparison, Figure 9 summarizes the rise time, settling time, overshoot, and SSE values obtained by each controller under the four operating scenarios. As shown in Figure 9(a) and Figure 9(b), the proposed IFTSMC controller generally achieves the shortest rise and settling times, indicating faster transient response and rapid stabilization. Similarly, Figure 9(c) demonstrates that the overshoot associated with IFTSMC remains significantly lower than that of PI, SMC, TSMC, and FTSMC. Moreover, Figure 9(d) confirms that the proposed method consistently produces the lowest SSE, ensuring highly accurate speed tracking and improved steady-state performance.

The superior performance of the proposed IFTSMC controller can be attributed to its advanced control structure and finite-time convergence characteristics. The improved fast terminal sliding surface accelerates the reduction of speed-tracking errors, enabling the system to reach the desired operating point within a shorter time. Consequently, the controller achieves faster transient response, reduced rise time, and shorter settling time. Furthermore, the control law combines robust compensation with nonlinear convergence terms, allowing the controller to effectively suppress chattering while maintaining strong resilience against parameter uncertainties, load disturbances, and operating-condition variations. These features contribute to minimal overshoot and low steady-state error, resulting in highly accurate speed regulation. In contrast, conventional SMC provides good robustness but often suffers from chattering due to its discontinuous switching mechanism. Although it improves disturbance rejection compared with classical controllers, it still exhibits relatively larger overshoot and higher steady-state error than the proposed approach. Similarly, the PI controller is limited in handling the nonlinear dynamics of BLDC motors and is less effective under significant load and speed variations. As a result, PI control generally produces slower dynamic response, larger overshoot, longer settling time, and reduced tracking accuracy.

The TSMC and FTSMC methods overcome several shortcomings of PI and conventional SMC through finite-time convergence and nonlinear sliding surface formulations. However, the proposed IFTSMC further refines these concepts by introducing an enhanced sliding surface and improved control mechanism that accelerate convergence while preserving robustness. This leads to lower overshoot, faster stabilization, improved disturbance rejection capability, and reduced steady-state error compared with TSMC and FTSMC. Therefore, the performance improvements observed in Table 4 and the responses illustrated in Figures 4–9 are consistent with the theoretical foundations of the proposed controller. The results confirm that IFTSMC provides the most effective balance between speed, stability, robustness, and tracking accuracy, making it a highly suitable solution for high-performance BLDC motor speed control applications.

Despite the promising results achieved by the proposed IFTSMC controller, certain limitations should be considered. The controller employs a nonlinear control structure and finite-time convergence mechanism, which increases computational complexity compared with conventional PI and SMC approaches. Consequently, real-time implementation on low-cost embedded platforms with limited processing capability may present challenges. In addition, the performance of the controller is influenced by the appropriate selection of design parameters such as k1, k2, and α. Determining optimal parameter values for different operating conditions may require extensive tuning and validation. Furthermore, the present study primarily focuses on simulation-based evaluation under predefined speed commands and load disturbances. The behavior of the controller under severe nonlinearities, parameter uncertainties, and extreme operating conditions requires further investigation to fully assess its robustness and practical applicability. Future research may focus on the development of adaptive or intelligent parameter-tuning mechanisms capable of automatically adjusting controller gains in real time according to changing operating conditions. The integration of optimization algorithms and artificial intelligence techniques could further enhance controller performance while reducing tuning effort. Additional work may also explore computational simplification strategies to facilitate implementation on resource-constrained embedded systems. Experimental validation using hardware prototypes and real-time digital control platforms is another important direction to verify the effectiveness of the proposed approach under practical operating environments. Moreover, extending the IFTSMC framework to sensorless BLDC motor drives, multi-motor systems, electric vehicle propulsion systems, and other advanced industrial applications may further broaden its applicability and demonstrate its effectiveness in complex control scenarios.

5. CONCLUSION

This study presented an Improved Fast Terminal Sliding Mode Control (IFTSMC) strategy for high-performance speed regulation of BLDC motors. The proposed controller was designed to enhance dynamic response, tracking accuracy, and robustness under varying load conditions and reference-speed commands. To evaluate its effectiveness, the BLDC motor drive system was subjected to four different operating scenarios involving speed variations and load disturbances. The performance of the proposed controller was compared with conventional PI, SMC, TSMC, and FTSMC approaches using rise time, settling time, overshoot, and steady-state error (SSE) as evaluation criteria. The simulation results demonstrated that the proposed IFTSMC controller consistently provides superior performance across all investigated case studies. The controller achieved faster convergence, shorter settling time, lower overshoot, and improved tracking accuracy compared with the conventional PI and SMC methods. For example, in Case Study 2, the IFTSMC controller limited the overshoot to only 0.006%, whereas PI and SMC produced overshoots of 13.13% and 1.30%, respectively. Similarly, the SSE obtained with IFTSMC was significantly lower than that of the conventional controllers, confirming its ability to maintain accurate speed tracking under dynamic operating conditions. Furthermore, when compared with advanced nonlinear controllers such as TSMC and FTSMC, the proposed IFTSMC approach exhibited improved transient response and enhanced robustness while maintaining finite-time convergence characteristics. The improved sliding surface and control law effectively reduced chattering, minimized tracking error, and enhanced disturbance rejection capability. These advantages make the proposed controller particularly suitable for applications requiring precise speed regulation and reliable operation under varying load conditions.

REFERENCES:

[1] C. P. Reddy, M. Jayakumar, K. Raj, S. Kishore, and S. S. Pandey, “Development of BLDC motor controller using sensor-based method,” in Proc. 2nd Int. Conf. Emerging Trends in Information Technology and Engineering (ICETITE), 2024, pp. 1–6.

[2] O. Ammari, K. El Majdoub, F. Giri, R. Baz, “Comprehensive modeling and simulation of longitudinal dynamics in electric vehicles with in-wheel BLDC motors: Integration of chassis, motor, inverter, and Tire-Pacejka model,” J. Control Autom. Electr. Syst., vol. 36, no. 1, pp. 147–164, 2025.

[3] G. Kaczmarczyk, M. Malarczyk, D. D. Ferreira, and M. Kaminski, “Stable rules definition for fuzzy TS speed controller implemented for BLDC motor,” Appl. Sci., vol. 14, no. 3, p. 982, 2024.

[4] A. Kanungo, C. Choubey, V. Gupta, P. Kumar, and N. Kumar, “Design of an intelligent wavelet-based fuzzy adaptive PID control for brushless motor,” Multimed. Tools Appl., vol. 82, no. 21, pp. 33203–33223, 2023.

[5] S. Patel, S. Yadav, and N. Tiwari, “Performance improvement of BLDC motor driven electric vehicle using different metaheuristic optimisations based techniques,” Int. J. Powertrains, vol. 13, no. 3, pp. 248–268, 2024.

[6] Y. Wang and H. Wang, "Research on control technology of brushless DC motor for robot," in Proc. 8th Int. Conf. Control Engineering and Artificial Intelligence, 2024, pp. 188–193.

[7] S. B. Abdi, A. Debilou, A. Guergazi, Y. Samsar, and M. Labed, "Speed control of BLDC quadrotor motor using an ANN trained with PID controller data optimized by PSO algorithm," in Proc. 8th Int. Conf. Image and Signal Processing and their Applications (ISPA), 2024, pp. 1–7.

[8] W. Kong et al., "PID control algorithm based on multistrategy enhanced dung beetle optimizer and back propagation neural network for DC motor control," Sci. Rep., vol. 14, no. 1, Art. no. 28276, 2024.

[9] G. Taş and M. Özdamar, "Estimation of PID parameters of BLDC motor system by using machine learning methods," Signal Image Video Process., vol. 19, no. 1, p. 140, 2025.

[10] H. Maghfiroh, A. Ramelan, and F. Adriyanto, "Fuzzy-PID in BLDC motor speed control using MATLAB/Simulink," J. Robot. Control, vol. 3, no. 1, pp. 8–13, 2022.

[11] C. Uyulan and E. Arslan, "Sliding mode-based traction control system design for electric scooter BLDCM through field-oriented vector control approach," Dokuz Eylül Univ. Müh. Fak. Fen ve Müh. Derg., vol. 25, no. 74, pp. 433–450, 2022.

[12] F. Bodur and O. Kaplan, "Integral sliding mode control with improved reaching law for brushless DC motor speed control," in Proc. 11th Int. Conf. Smart Grid (icSmartGrid), 2023, pp. 1–7.

[13] A. Mousmi, A. Abbou, and Y. El Houm, "Real-time implementation of a novel hybrid fuzzy sliding mode control of a BLDC motor," Int. J. Power Electron. Drive Syst., vol. 10, no. 3, p. 1167, 2019.

[14] J. R. B. de A. Monteiro, C. M. R. de Oliveira, and M. L. de Aguiar, "Sliding mode control of brushless DC motor speed with chattering reduction," in Proc. IEEE 24th Int. Symp. Industrial Electronics (ISIE), 2015, pp. 542–547.

[15] M. Topal, I. Iskender, and N. Genc, "Sensorless speed control of a BLDC motor using improved sliding mode observer technique," Int. J. Tech. Phys. Probl. Eng., vol. 11, no. 1, pp. 1–9, 2019.

[16] A. Mamadapur and G. U. Mahadev, "Speed control of BLDC motor using neural network controller and PID controller," in Proc. 2nd Int. Conf. Power and Embedded Drive Control (ICPEDC), 2019, pp. 146–151.

[17] Y. Guo and M. E. A. Mohamed, "Speed control of direct current motor using ANFIS based hybrid PID configuration controller," IEEE Access, vol. 8, pp. 125638–125647, 2020.

[18] D. X. Ba, H. Yeom, J. Kim, and J. Bae, "Gain-adaptive robust backstepping position control of a BLDC motor system," IEEE/ASME Trans. Mechatronics, vol. 23, no. 5, pp. 2470–2481, 2018.

[19] N. Hemalatha, S. Venkatesan, R. Kannan, S. Kannan, A. Bhuvanesh, and A. Kamaraja, "Sensorless speed and position control of permanent magnet BLDC motor using particle swarm optimization and ANFIS," Measurement: Sensors, vol. 31, Art. no. 100960, 2024.

[20] I. Anshory, D. Hadidjaja, and R. B. Jakaria, "BLDC motor: Modeling and optimization speed control using firefly algorithm," Dinamik, vol. 25, no. 2, pp. 51–58, 2020.

[21] P. Dutta and S. K. Nayak, "Grey wolf optimizer based PID controller for speed control of BLDC motor," J. Electr. Eng. Technol., vol. 16, pp. 955–961, 2021.

[22] K. Vanchinathan and K. Valluvan, "A metaheuristic optimization approach for tuning of fractional-order PID controller for speed control of sensorless BLDC motor," J. Circuits Syst. Comput., vol. 27, no. 8, Art. no. 1850123, 2018.

[23] S. S. A. Naqvi et al., "Multi-objective optimization of PI controller for BLDC motor speed control and energy saving in electric vehicles: A constrained swarm-based approach," Energy Rep., vol. 12, pp. 402–417, 2024.

[24] S. Bazi, R. Benzid, Y. Bazi, and M. M. A. Rahhal, "A fast firefly algorithm for function optimization: Application to the control of BLDC motor," Sensors, vol. 21, no. 16, p. 5267, 2021.

[25] K. Vanchinathan, K. Valluvan, C. Gnanavel, and C. Gokul, "Design methodology and experimental verification of intelligent speed controllers for sensorless permanent magnet brushless DC motor," Int. Trans. Electr. Energy Syst., vol. 31, no. 9, Art. no. e12991, 2021.

[26] A. Intidam et al., "Development and experimental implementation of optimized PI-ANFIS controller for speed control of a brushless DC motor in fuel cell electric

vehicles," Energies, vol. 16, no. 11, p. 4395, 2023.

[27] R. Arivalahan, S. Venkatesh, and T. Vinoth, "An effective speed regulation of brushless DC motor using hybrid approach," Adv. Eng. Softw., vol. 174, Art. no. 103321, 2022.

[28] V. Bogdan, M. Adrian, L. Leonard, B. Alexandra, S. Alecsandru, and N. Ionut, "Design and optimization of a BLDC motor for small power vehicles," in Proc. Int. Conf. Electromechanical and Energy Systems (SIELMEN), 2021, pp. 438–443.

[29] A. M. Jarkas and M. Doss, "Optimized PI controller tuning for improved performance in BLDC motor speed control using heuristic adaptive lyrebird optimization algorithm," Electrical Engineering, pp. 1–21, 2025.

[30] L. Chen et al., "Sensorless fixed-time sliding mode control of PMSM based on barrier function adaptive super-twisting observer," IEEE Trans. Power Electron., vol. 39, no. 3, pp. 3037–3051, 2023.

[31] K. Shao, J. Zheng, H. Wang, X. Wang, R. Lu, and Z. Man, "Tracking control of a linear motor positioner based on barrier function adaptive sliding mode," IEEE Trans. Ind. Informatics, vol. 17, no. 11, pp. 7479–7488, 2021.

[32] V. Kumarasamy, V. Karumanchetty Thottam Ramasamy, G. Chandrasekaran, G. Chinnaraj, P. Sivalingam, and N. S. Kumar, "A review of integer order PID and fractional order PID controllers using optimization techniques for speed control of brushless DC motor drive," Int. J. Syst. Assur. Eng. Manag., vol. 14, no. 4, pp. 1139–1150, 2023.

[33] N. Prabhu, R. Thirumalaivasan, and B. Ashok, "Design of sliding mode controller with improved reaching law through self-learning strategy to mitigate the torque ripple in BLDC motor for electric vehicles," Comput. Electr. Eng., vol. 118, Art. no. 109438, 2024.

[34] W. J. N. Goto, D. W. Bertol, and N. A. Martins, "Formation and trajectory tracking of mobile robots with uncertainties and disturbances using an adaptive immune fuzzy quasi-sliding mode control," J. Control Autom. Electr. Syst., vol. 35, no. 3, pp. 440–460, 2024.

[35] L. Zhang, R. Tao, Z.-X. Zhang, Y.-R. Chien, and J. Bai, "PMSM non-singular fast terminal sliding mode control with disturbance compensation," Inf. Sci., vol. 642, Art. no. 119040, 2023.

[36] P. Kumar, D. V. Bhaskar, R. K. Behera, and U. R. Muduli, "Continuous fast terminal sliding surface-based sensorless speed control of PMBLDCM drive," IEEE Trans. Ind. Electron., vol. 70, no. 10, pp. 9786–9798, 2022.

[37] P. Kumar, A. B. Beig, K. Al Jaafari, D. V. Bhaskar, R. K. Behera, and U. R. Muduli, "Continuous fast terminal sliding surface-based interrupt free operation of PMBLDCM drive," in Proc. IECON 2023–49th Annual Conf. IEEE Industrial Electronics Society, 2023, pp. 1–6.

[38] G. Balta, N. Güler, and N. Altin, "Global fast terminal sliding mode control with fixed switching frequency for voltage control of DC–DC buck converters," ISA Trans., vol. 143, pp. 582–595, 2023.

[39] O. M. Neda, "A dual placement strategy for DG and D-STATCOM units using multi-objective optimization in an Iraqi radial distribution system," Expert Syst. Appl., vol. 299, Art. no. 130230, 2026.