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RESEARCH ARTICLE

A Comparative Study of Advanced PID and Advanced SMC Controllers for Robust Speed Control of BLDC Motor

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ABSTRACT

There are several industrial applications for BLDC motors where precise speed control is required. There has been a lot of research on and practical use of classical controllers, but when dealing with nonlinearity, changing plant parameters, moving time delays, and excessive plant noise, advanced controllers often perform better. This research compares two different methods for controlling the BLDC motor drive system speed. An advanced Sliding Mode Controller based on the super-twisting method with integral sliding surface and an advanced Proportional Integral Derivative (PID) controller with derivative filtering and anti-windup compensation are both examined in this work. The author of this study examines a BLDC motor model and evaluate both controllers under identical conditions in MATLAB/Simulink. The simulation's results show that both controllers exhibit a low steady-state error and dependable speed control. The SMC converges faster than the PID controller, whereas PID is simpler to develop computationally and has smoother control action. Performance metrics are examined to assess the dynamic response. The simulation results indicated that with settling times of less than 0.6 seconds, both controllers exhibit comparable transient responses. The SMC controller achieves a low steady state error of 0.3164 RPM compared to 2.3758 RPM for the PID controller, while also reducing chattering level and control efforts. The simulation results elaborated that both controllers are good choices in controlling motor speed and attaining precise reference tracking.

Keywords: BLDC motor, Advanced sliding mode controller, Advanced PID control, Robust control

1. Introduction

Brushless DC (BLDC) motors are becoming more common in some applications, such as transportation, industrial automation, renewable energy systems, and robotics, because of their good performance and longer lifespan [1]. BLDC motors use position sensors in conjunction with a digital converter to improve performance, lower noise, and increase longevity since they avoid the mechanical commutation effect. In terms of efficiency, torque-to-weight ratio, and noise level, BLDC motors are expected to perform better than conventional motors. Despite rapid advances in control theory, industry still frequently uses the conventional Proportional-Integral-Derivative controller. For a correct operation, control and feedback mechanisms must be dependable and effective [2]. Unwanted torque ripples and speed changes may result from a single commutation or an inaccurate torque measurement. Related possible problems include nonlinear dynamics, electric torque ripple, load disturbances, parameter changes, and incorrect BLDC motor speed control. For motors to operate consistently and dependably under a variety of operating situations, complex control systems are required [3].

Traditional PID controllers are being used more often to regulate BLDC motors due to their convenience of use [4, 5]. By adjusting the derivative, integral, and proportional gains, PID controllers can regulate the system's dynamics. Numerous studies have

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Table . List of Abbreviations

Abbreviation	Description
BLDC	Brushless Direct Current
PID	Proportional Integral Derivative
ANFIS	Adaptive Neuro-Fuzzy Inference Systems
SMC	Sliding Mode Control
SSE	Steady-State Error
FVS	Fuzzy Variable Structure
EMF	Electromotive Force
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute

demonstrated that PID-based speed control using simulation tools like MATLAB/Simulink can enhance the transient responsiveness and steady-state performance of BLDC motors [6]. Conversely, traditional PID controllers might not handle nonlinear operating conditions, adjust parameters efficiently, or introduce uncertainty into the system. To work with complex PID controllers that can get around these limitations, researchers have explored a range of adaptive processes, such as fractional-order PID, gain scheduling, anti-windup compensation, and optimization-based tuning strategies. These improvements improve the controller's resilience and dynamic performance in nonlinear systems, including BLDC motor drives.

Sliding Mode Control (SMC) is also another effective control method [7]. Despite the robustness of SMC, actuator degradation can results from chattering effects. This nonlinear control approach has gained considerable recognition for its robustness against external perturbations and parameter uncertainty. In an effort to enhance system performance and decrease the chattering issues caused by first-order SMC, more advanced forms of SMC, for example, terminal SMC, higher-order SMC, super-twisting algorithms, and integral SMC, have been studied [8]. Applications requiring fast dynamic response and excellent durability are ideal for these controllers. Hence, motivated by these advantages and challenges, this paper has primarily contributed to the design and implementation of the advanced versions of PID and SMC controllers for BLDC motor speed control. The suggested controllers offer rapid convergence, reduced steady-state error (SSE), and enhanced dynamic performance. When comparing PID and SMC-based controllers, the simulation results demonstrate the effectiveness of both approaches.

Electrical motors serve as the most important component of both industrial and household automation due to their compact size, ease of control, efficiency, and flexibility in handling various workloads [9]. Because of their superior thermal properties, higher torque-to-weight ratio, and reduced maintenance needs, BLDC motors are favored. Accurately controlling the speed of motors under nonlinear circumstances and load fluctuations, however, is a difficult challenge.

Several recent studies have focused on improving the speed regulation of BLDC motors using PID-based control approaches. Ref. [10] proposed an adaptive fuzzy-PID controller that fine-tunes controller gains in response to system operating parameters. Likewise, PID performance has been enhanced with the application of optimization techniques [11]. Ref. [12] used MATLAB/Simulink to evaluate traditional PID controllers for BLDC motor speed control. Furthermore, studies comparing different controller types for BLDC motor systems have shown that hybrid techniques, like fuzzy-PID controllers, provide better dynamic features [13]. Intelligent [14] and hybrid control systems have recently used optimization techniques and neural networks to enhance BLDC motor speed control [15, 16]. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Fuzzy logic controller (FLC) offer efficient nonlinear mapping and flexibility by fusing rule-based inference with learning mechanisms. [17]. A study investigates a methodology that applies ANFIS to BLDC motor speed control [18]. To compare the system performance to that of conventional controllers such as proportional integral, PID, and fuzzy variable structure (FVS), extensive simulations are done using Simulink. A neuro-fuzzy controller overseen by fuzzy critic logic was designed for BLDC motors [19]. The performance of the control system is affected by any changes made to the PID controller. Recursive least squares and error back propagation were two of the online mixed learning techniques used by the authors of the study [20] to train a neuro-fuzzy system.

Due to its inherent resistance to external perturbations and parameter changes, SMC [21] has become more well-known [22]. However, the main limitation of SMC is the high-frequency chattering effect, which can limit actuator life and generate mechanical stress [23]. SMC-based controllers for BLDC motors offer better response times and disturbance rejection, according to the research. Additional research on several SMC variants, including incorporated SMCs, first-order and second-order SMCs, and BLDC drive systems for electric automobiles, has demonstrated enhanced stability and robustness. One study includes the introduction of a fast terminal SMC approach for BLDC motor speed regulation, which greatly improves its dynamic performance [24]. Additional research has focused on super-twisting SMC, an improved SMC algorithm that strengthens and improves the tracking accuracy of BLDC motor control systems [25]. Researchers have shown that by comparing different control strategies, like PID-based and nonlinear

controllers, new control techniques can substantially boost the total performance and efficiency of BLDC motor drives in modern energy and transportation systems [26].

The objective of this research is to examine and contrast two different contemporary control strategies for a BLDC motor's speed regulation. Developing and implementing a unified simulation framework for speed control of BLDC motor, composed of an advanced PID-based controller and an advanced SMC, is the primary objective of the study. To maintain parity in comparison, both controllers were developed and tested with identical motor parameters. Moreover, the proposed study analyzes the two controllers' dynamic performance utilizing key performance indicators.

The outline of the remaining paper is as follows: Section 2 details the mathematical modeling and design approach for the BLDC motor and both controllers. The implementation and MATLAB/Simulink results are described in Section 3, which also contrasts this work with other related efforts in the literature. The study is concluded in Section 4 with recommendations for future research.

2. Materials and methods

This section presents the BLDC motor modeling and the design of the proposed controllers. The electromechanical dynamics form the foundation of the control system design study. Assuming symmetrical stator windings and low phase-to-phase mutual inductance, this is the electrical model of the motor.

$$V_a = L\frac{di_a}{dt} + e_a + Ri_a \tag{1}$$

$$V_b = L\frac{di_b}{dt} + e_b + Ri_b \tag{2}$$

$$V_c = L\frac{di_c}{dt} + e_c + Ri_c \tag{3}$$

where the phase voltages are denoted by V_a, V_b, V_c; i_a, i_b, i_c represent the corresponding phase currents; whereas; e_a, e_b, e_c denote the back EMFs induced by the rotor's motion [27].

Eq. (4) states motor electromagnetic torque (T_e):

$$T_e = \frac{1}{\omega_e}(e_a i_a + e_b i_b + e_c i_c) \tag{4}$$

where ω_e represents electrical angular speed.

The mechanical behaviour of the rotor is described by:

$$J\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \tag{5}$$

Where J denotes the moment of inertia, B represents the viscous damping coefficient, ω_r represents the mechanical rotor speed, and T_L denotes the load torque. When the applied voltage is balanced with the torque T_e and the resulting speed induces a back-EMF, the BLDC motor's overall electromechanical reaction can be represented by Eqs. (1) to (5) [28]. Regardless of changes in load or parameter uncertainty, a well-regulated speed should be maintained by a control system that ensures the rotor speed consistently tracks the reference signal. The detailed methodology followed in the study is given in Fig. 1.

2.1. Advanced PID controller implementation

The control law in the time domain for the classical PID controller is defined as:

$$u(t) = K_p e(t) + K_d\frac{de(t)}{dt} + K_i\int e(t)\,dt \tag{6}$$

In the above equation, $e(t) = \omega_{\text{ref}}(t) - \omega(t)$ is the speed error, whereas, K_p, K_i, and K_d denotes the proportional, integral, and derivative gains of the controller, respectively. In the Laplace domain, Eq. (6)

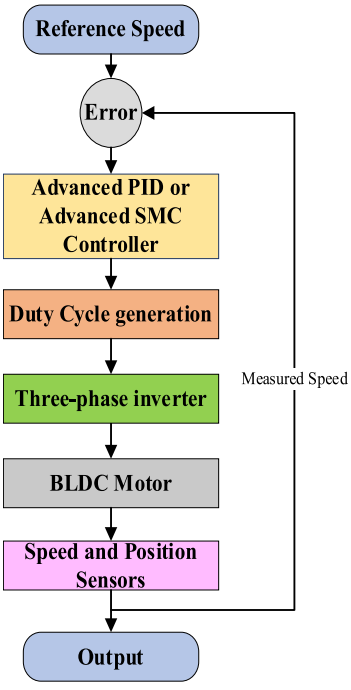


Fig. 1. Proposed control framework for BLDC speed control.

may be expressed as:

$$G_C(s) = K_p + \frac{K_i}{s} + K_d s \tag{7}$$

The inverter modifies the stator phase currents to produce the required torque, and receives a reference voltage signal from the controller output. To stabilize the required rotor speed, the feedback loop continuously adjusts the control effort. In this study, a more advanced PID controller is employed to improve robustness and reduce real-world limitations such as integrator windup and noise amplification. Back-calculation anti-windup correction and a filtered derivative term are included in the implemented controller. To reduce measurement noise, the derivative action is filtered:

$$D_f(s) = \frac{s}{\tau s + 1} \tag{8}$$

Before saturation, the control signal is written as:

$$u_{unsatur} = K_p e + K_i z + K_d d_f \tag{9}$$

Because the control signal is implemented as a PWM duty cycle, it must be restricted within physical limitations. A back-calculation anti-windup strategy is used to prevent integrator windup caused by actuator saturation:

$$\dot{z} = e + k_{aw}(u - u_{unsatur}) \tag{10}$$

In the above equations, z is the integral state, d_f is the filtered derivative, and k_{aw} denotes anti-windup gain. These adjustments result in a reliable PID controller suitable for use with nonlinear motor drive systems. In the Laplace domain, the entire closed-loop system can be written as:

$$T(s) = \frac{G_C(s) * G_p(s)}{1 + G_p(s) * G_C(s)} \tag{11}$$

where $G_p(s)$ denotes the BLDC motor transfer function obtained, after linearization about the normal operating region. The criteria state that the system stays stable if the open-loop transfer function, which is $G_{OL}(s) = G_m(s)G_c(s)$, satisfies:

$$\angle G_{OL}(j\omega) > -180^\circ \text{ when } |G_{OL}(j\omega)| = 1 \tag{12}$$

and,

$$Gain\ Margin\ (GM)\ and\ Phase\ Margin\ (PM) > 0 \tag{13}$$

These stability margins demonstrate the PID controller's resilience and stability in the face of parameter changes and load disruptions. By reducing high-frequency ripple and limiting low-frequency sensitivity, the open-loop system guarantees unity gain and flat phase at the chosen crossover.

2.2. Advanced SMC approach implementation

By creating a suitable sliding surface and enforcing a reaching condition, SMC ensures stability. The selection of an integrated sliding surface is as follows:

$$\sigma = \lambda \int e\, dt + e \tag{14}$$

Where $\lambda > 0$, it denotes the sliding surface gain and is the design parameter.

Taking the derivative of Eq. (14), the sliding surface results:

$$\dot{\sigma}(t) = \dot{e}(t) + \lambda e(t) \tag{15}$$

The objective of the controller is to get the sliding surface to a point where the speed error is also close to zero. A higher-order sliding- mode technique, the super-twisting algorithm, is employed to decrease chattering. It is defined as the switching control component. The switching function is defined as:

$$\mathrm{s} = \tanh\left(\frac{\sigma}{\phi}\right) \tag{16}$$

where ϕ denotes boundary layer thickness parameter. Thus, the modified super-twisting control law becomes:

$$u_{ust} = k_1\sqrt{|\sigma|}\mathrm{s} + k_2 z \tag{17}$$

and

$$\dot{z} = \mathrm{s} \tag{18}$$

where k_1 and k_2 are switching gains of the super-twisting algorithm, s is a continuous switching function, and z is an auxiliary control variable. Hence, the final control law applied becomes:

$$u = u_0 + u_{ust} \tag{19}$$

where u_0 is nominal control input. The practical implementation of the control signal is ensured by limiting its duty cycle to an acceptable range. These updates have improved the BLDC motor's speed management, reduced chattering, and accelerated convergence.

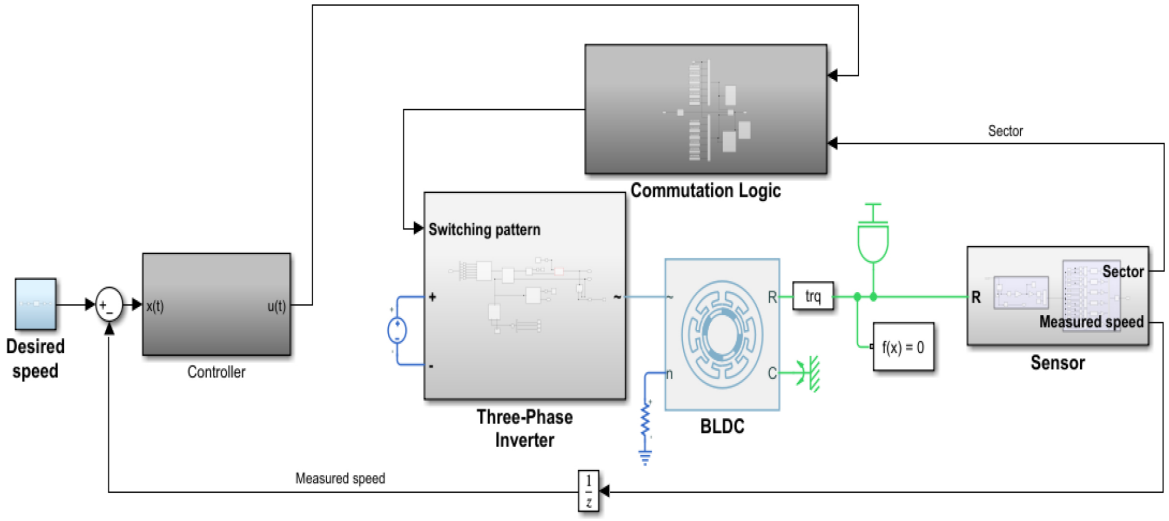


Fig. 2. Simulink model for speed control of BLDC motor.

To access system stability, a positive definite Lyapunov function is chosen:

$$V = \frac{1}{2}\sigma^2 \tag{20}$$

An expression for the Lyapunov function's derivative is:

$$\dot{V} = \sigma\dot{\sigma} \tag{21}$$

Under super-twisting control law, for the ideal case, the dynamics of the sliding variable can be described using the conventional super-twisting structure as:

$$\dot{\sigma} = -k_1\sqrt{|\sigma|}s + z + d(t) \tag{22}$$

Where d(t) is a bounded lumped uncertainty or disturbance term, which is assumed to be bounded.

$$d(t) \leq D \tag{23}$$

where D is a positive constant denoting the maximum uncertainty bound.

Substituting the sliding surface dynamics into Lyapunov derivatives yields;

$$-k_1\sigma\sqrt{|\sigma|}s < 0 \tag{24}$$

Consequently, the reaching condition is satisfied. When the gains dominate the bounded disturbance, we obtain:

$$\dot{V} \leq -\eta|\sigma| \tag{25}$$

For some $\eta > 0$, therefore $\sigma \to 0$ and $e \to 0$. This ensures that the sliding surface converges and that the tracking error thereafter decreases.

3. Results and discussion

Fig. 2 is the model used to simulate the BLDC Motor speed control system in MATLAB/Simulink [29]. An advanced PID controller with derivative filtering and anti-windup compensation, and an advanced SMC based on the super-twisting algorithm with an integral sliding surface were both used as control methods. The simulation model includes a three-phase inverter, a BLDC motor model, commutation logic, position and speed sensors for the feedback loop, the required speed reference, and controller blocks. Table 1 summarizes the BLDC motor

Table 1. BLDC motor parameters and simulation solver settings.

Parameters	Value
Type of Winding	Wye Wound
Number of poles/pair	4
Back–EMF Profile	Perfect trapezoid
Motor Speed	1750 RPM
Stator Per-phase inductance	0.0001 H
Load Inertia	2 Kg m2
Stator Per-phase resistance	0.001 Ω
Rotor Damping Coefficient	0.1 N.m(rad/s)
Permanent Magnet Flux Linkage	0.18 Wb
DC-Link Voltage	500 V
PWM switching frequency	1k Hz
Sampling Time	5 x 10^{-5}s
Simulation Time	1 s
Solver Type	Variable-step
Solver	odeN (Nonadaptive)
Integration Method	ode3 (Bogacki-Shampine)

Table 2. Advanced PID controller parameter values.

Parameters	Value
$\mathbf{K_p}$	1.5
$\mathbf{K_i}$	100
$\mathbf{K_d}$	0.1
Derivative filter constant (τ)	0.06
Anti-windup gain ($\mathbf{k_{aw}}$)	200
Sampling Time	5 x 10^{-5}

Table 3. Advanced SMC parameters.

Parameters	Value
Sliding surface gain	30
Boundary layer constant	100
$\mathbf{k}_1$	0.5
$\mathbf{k}_2$	0.9
Initial duty cycle	0.2
Duty rate limit	0.01

model's parameters and simulation solver settings. The mechanical and electrical properties of the motor utilized in the simulation are defined by these parameters.

The desired RPM command is produced by the desired (reference) speed block. The error is given as input to the controller block, and it outputs a control signal. The controller output generates a duty-cycle signal that is sent to the commutation logic block. Based on the duty cycle and the rotor position feedback from the sensor signals, the commutation logic selects the appropriate switching sequence for the 3-phase inverter. The T_e and motor rotor speed are then controlled by the inverter, which energizes the motor windings in accordance with the active sector. Table 2 lists the advanced PID controller's parameters employed in the research for the specific configuration. After adjusting the controller to provide steady speed tracking while reducing overshoot and settling time, these settings were chosen.

Similarly, Table 3 shows the parameter values for the advanced SMC. These parameters govern the behavior of the super-twisting sliding mode algorithm as well as the smooth switching function used in the control law.

The switching sequence to be employed to the BLDC motor is determined by the commutation logic block using the duty cycle output of the controller and the feedback from the Hall sensor block. When the duty cycle is $< 50\%$, a specific switching strategy is employed to lower the speed. According to the timing diagram, if the duty cycle is greater than 50%, the BLDC motor's speed is increased using a different switching mechanism. The target speed signal and the current speed error are compared to determine the control voltage. In order to ensure that the inverter switches in the correct sequence, the commutation logic utilizes data from the Hall sensors. By adjusting the time of phase excitation in response to changes in the amount of the control signal, the inverter allows for the rotor to be slowed down or accelerated to keep its speed precisely synchronized.

Fig. 3 illustrates BLDC motor's speed response using an advanced PID controller. The simulation results show that the motor can accurately match the reference speed with SSE. The advanced PID controller's stable response, demonstrated by the transient behavior, is achieved through derivative filtering and anti-windup algorithms. Because of these characteristics, the control action is smooth when the speed is changed, and excessive oscillations are prevented.

Under advanced PID control, the BLDC motor torque response is demonstrated in Fig. 4. The minor ripple components in the torque waveform are mainly caused by the inverter's switching action and the commutation properties of the BLDC motor. Regardless of these fluctuations, torque variations remain within acceptable limits and do not affect the opera-

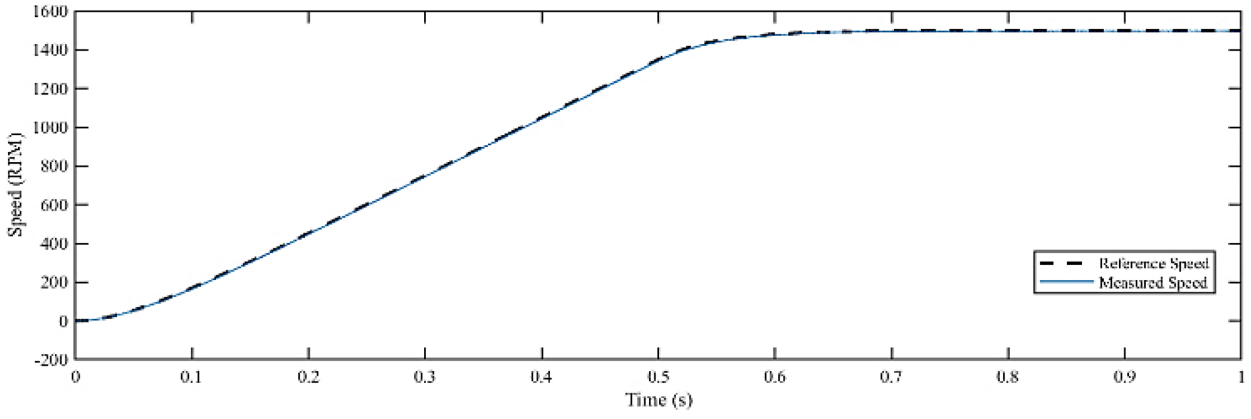


Fig. 3. Speed response with an advanced PID controller.

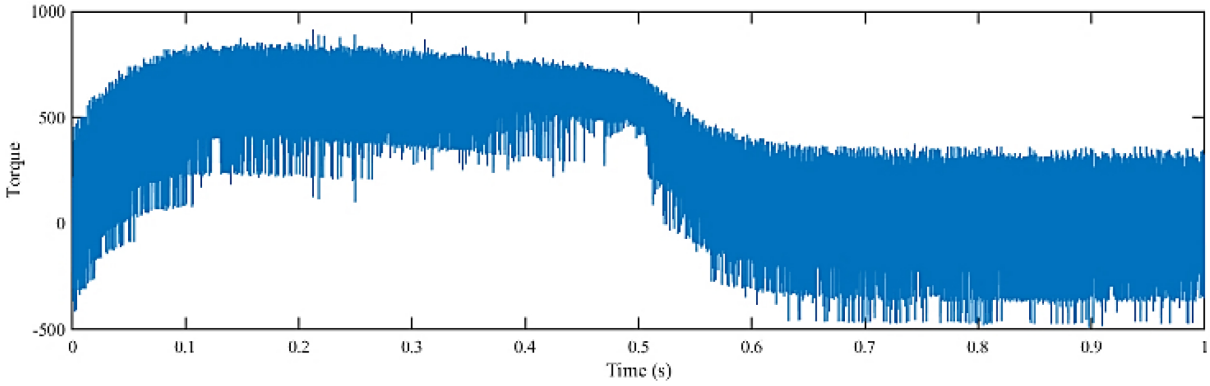


Fig. 4. Electromagnetic torque response using an advanced PID.

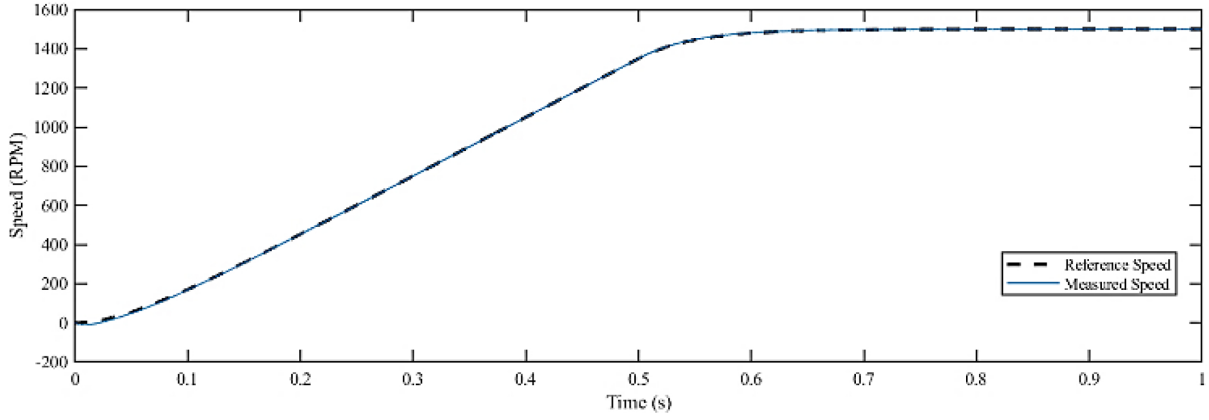


Fig. 5. Speed response of BLDC motor using advanced SMC.

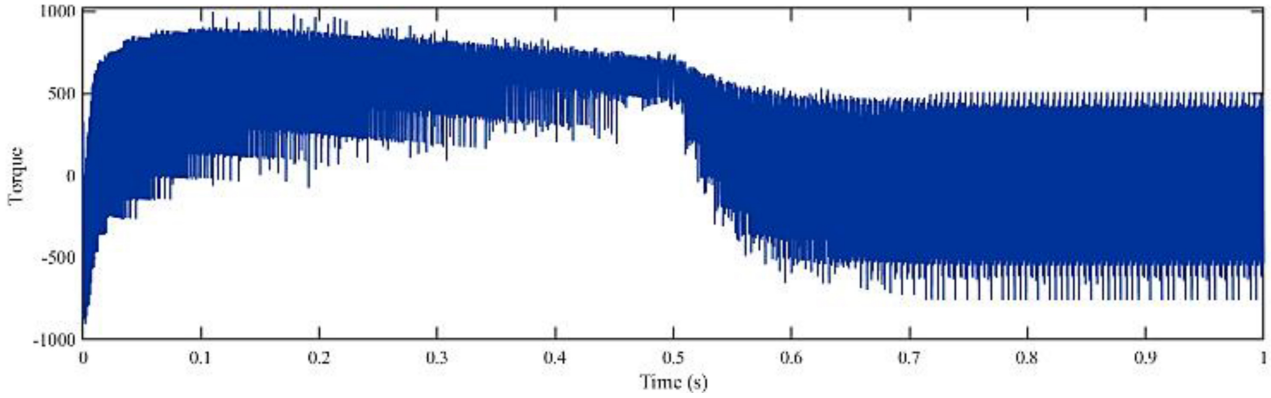


Fig. 6. Electromagnetic torque response with advanced SMC.

tion of the speed regulation. Thus, having a controller in place ensures that the motor operates reliably and generates consistent torque throughout the simulation.

The speed response of the BLDC motor with advanced SMC implementation is depicted in Fig. 5. The results demonstrate that the SMC achieves the reference speed faster than the PID controller. The response exhibits improved dynamic performance, with rapid error convergence and outstanding robustness despite disruptions. A smooth switching function based on the hyperbolic tangent function effectively reduces the chattering phenomenon typically associated with SMC.

The response of the SMC to electromagnetic torque is seen in Fig. 6. Minimal torque ripples are an effect of BLDC commutation and inverter switching, just as they are in a PID scenario. Nonetheless, the controller

Table 4. Performance metrics with two different advanced controllers.

Controller	T_r (s)	T_s(s)	SSE	Overshoot (%)	Chattering Level	Control Effort
PID	0.4083	0.5823	2.3758	0	0.29	0.816
SMC	0.4069	0.5774	0.3164	0.0678	0.016	0.762

Table 5. Comparison and summary of some similar studies.

Ref.	Controller/Approach//Methodology	Key Takeaways
[30]	Higher Order SMC, Lyapunov approach for system stability	SMC includes the chattering issue, but with robust tracking and improved settling time
[31]	Fuzzy, PID, and SMC, Comparative nonlinear control study	SMC shows better robustness and disturbance rejection
[32]	FOPID controller, Manual tuning in Simulink	Smooth speed, good reference tracking; lightweight model
This study	Advanced SMC and PID	SMC faster response; PID smoother control.

maintains a constant motor speed while effectively controlling the torque dynamics. The improved disturbance rejection capabilities and increased robustness of the sliding mode controller guarantee constant motor performance regardless of the presence of nonlinearities or changes in the parameters.

To statistically evaluate the efficacy of the two control strategies, several dynamic response parameters were evaluated. The evaluation results are summarized in Table 4, where T_r and T_s denote rise and settling time in seconds, respectively. The control effort is determined using the control signal's root mean square value, and the chattering level is calculated using the standard deviation of the steady-state control signal.

3.1. Comparison with related works

A qualitative comparison of the proposed approaches with previous research on BLDC motor speed regulation is shown in Table 5. Numerous methodologies, such as optimization-based control, intelligent learning techniques, hybrid neuro-fuzzy systems, and observer-based sensorless control strategies, have been studied recently. In contrast to existing methods, the proposed study evaluates two advanced control strategies in the same simulation environment: advanced PID control and super-twisting SMC. For BLDC motor speed regulation, this thorough analysis offers a clear comparison between classical and advanced control systems.

4. Conclusion

This study investigated improved PID and SMC techniques for BLDC motor speed control. To evaluate controllers under the same simulation conditions, a comprehensive model of the motor was simulated and evaluated. While the advanced SMC employed a super-twisting algorithm with an integrated sliding surface to enhance robustness and reduce chattering, the advanced PID controller used derivative filtering and anti-windup compensation to improve dynamic performance and prevent integrator saturation. Both controllers are efficient in controlling motor speed and attaining precise reference tracking with low steady-state error, according to the simulation results.

To further enhance system performance, future research may focus on applying advanced optimization techniques to adjust controller settings and on conducting experimental validation of the proposed controllers. Finally, the effectiveness of the proposed controllers in broader contexts can be tested across a variety of electromechanical systems, including permanent-magnet synchronous motors and electric-car drive systems.

Conflict of interest

The author declares no conflict of interest.

Author contributions

Conceptualization: ZA, Formal analysis: ZA, Investigation: ZA, Methodology: ZA, Software: ZA, Writing –original draft: ZA, Writing –review & editing: ZA.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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