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Optimal Fractional-Order PID Control for BLDC Motor Drives: A Robust and IOT-Enabled Approach

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Abstract: Brushless DC motors have a very wide range of applications in industrial automation, however traditional PID controllers cannot provide stability with nonlinear and noisy operating conditions. To overcome this, a novel optimized Nelder–Mead algorithm is employed for an intelligent control structure using a Fractional Order PID controller, targeting the minimization of the Integral Time-weighted Absolute Error (ITAE). The proposed NM-FOPID framework is benchmarked against industrial standards, including Ziegler–Nichols (ZN) and Cohen–Coon (CC) methods, as well as metaheuristic benchmarks like PSO and GA. Experimental validation under different loading conditions (0.5–2.0 kg·m²) showed substantial performance improvement over traditional PID control. The FOPID controller reduced overshoot from 48.3% (traditional PID) to 8.24%, reduced settling time from 31.8 s to 5.9 s (≈ 81% improvement), and raised damping ratio to 1.73, leading to more robustness against disturbances. A White-noise test and frequency-domain analysis also verified high gain stability with a 25° phase margin. The proposed FOPID-based control realizes 70–80% improvement in transient performance and noise robustness, providing an optimal, Industry 4.0-compatible solution to smart BLDC motor control. Finally, the framework is implemented on a Raspberry Pi platform with Firebase integration, providing a scalable Industry 4.0 solution. The IoT layer achieves a measured jitter of ±1.2 ms and an 85 ms cloud latency, successfully decoupling high-speed local regulation from remote monitoring. These findings confirm that the NM-optimized FOPID provides a resilient, energy-efficient, and practical alternative for high-performance electric drive systems.

Keywords: Brushless DC Motor, Pulse Width Modulation, Fractional Order PID Controller, Nelder–Mead (NM) Simplex Optimization Algorithm, Integral Time-Weighted Absolute Error (ITAE).

1. Introduction

Brushless DC motors are widely used in all types of industrial applications. Because of their efficiency, reliability, and compact size, they are suitable for all industries where high performance and control are required, such as manufacturing, aviation, and the automotive industry segments. Conventionally, PID controllers cannot provide optimum performance in such applications. Plant noise in real time can have an impact on the performance of these motors. Such noises can be produced in real time due to some disturbances such as mechanical vibration, supply voltage fluctuations, and electromagnetic noises. In order to achieve efficient working of these motors, control over these noises is an essential requirement. To address all such concerns, in this research, work will be carried out on the Fractional Order PID control of BLDC motors. The conventional speed/torque control function of a BLDC motor is performed using a PWM or PID control technique. The conventional control system suffers in terms of slow response, oscillations, and instability under varying load conditions. In conventional control systems, optimization of performance parameters for a particular operating condition may lead to poor performance at other operating conditions.

The advanced control mechanism for the BLDC motor control system is attracting researchers these days for specific industrial applications where precise tuning and control is required. Several studies have highlighted the advantages of fractional-order control techniques in dynamic systems. For instance, comparative MATLAB simulations by researchers have demonstrated that by increasing robustness and decreasing steady-state error, FOPID controllers perform better than classical PID controllers in applications like liquid level control and DC motor speed regulation [1]. Gain-scheduling techniques have also been integrated with FOPID controllers to enhance adaptability under shifting operating conditions, enabling seamless real-time controller parameter adjustment without discontinuities in control signals [2]. In a similar vein, it has been suggested that fractional second-order sliding mode control can eliminate chattering effects in electromechanical systems and improve robustness against system uncertainties [3].

Fractional-order controllers' efficacy in real-world industrial systems has been further proven by experimental validation. When compared to traditional integer-order controllers, FOPID controllers can dramatically lower process variability and control effort, according to comparative studies done in industrial flow control plants [4]. Researchers have looked into the use of FOPID controllers for BLDC motor speed regulation in the field of electric drives and electric vehicles (EVs), showing better adaptability to load variations and plant disturbances. The results demonstrate that the adaptive supervisory self-learning controller outperforms traditional methods by considerably reducing energy consumption, improving state of charge retention, and increasing energy recuperation. [5]. Additionally, to lower system complexity and cost while preserving dependable motor operation, sensorless BLDC control strategies utilizing back-EMF detection in conjunction with PWM techniques have been proposed [6]. It has also been reported that fractional-order $PI^{\lambda}D^{\mu}$ control structures improve BLDC motor drive systems' dynamic response and efficiency [7].

Fractional-order control methods have been used in more general optimization and energy management issues outside of motor control applications. Research on electric vehicle systems highlights how BLDC motors are increasingly integrated with sophisticated energy management and intelligent control strategies [8]. The superiority of FOPID controllers over conventional PID controllers in handling nonlinearities, disturbances, and parametric variations is further supported by extensive surveys conducted across various engineering domains [9].

Meta-heuristic optimization techniques have also been incorporated into FOPID controller design to enhance controller performance. For example, the Artificial Bee Colony with Predator Effect (ABCPE) algorithm has been proposed for fine-tuning FOPID parameters, exhibiting better transient response and faster convergence when compared to conventional ABC algorithms and standard optimization techniques like PSO [10]. When compared to conventional PID controllers, simulation and hardware implementations of FOPID-based BLDC motor controllers in electric vehicle applications have shown faster response times, increased stability, and decreased overshoot [11]. In order to improve operational efficiency in dynamic situations, smart energy management systems have also investigated hybrid optimization techniques that combine FOPID control with intelligent algorithms [12].

Despite the significant number of investigations conducted on the application of fractional-order controllers, various issues are yet to be addressed for the application of these controllers in BLDC motor drives. In many of the existing literature, much emphasis has been placed on the design and optimization of controllers rather than examining the robustness of the controller for real-time noise disturbances. In real-time environments, various types of disturbances may occur due to electromagnetic interference and mechanical vibration, resulting in stochastic noise effects on the stability of the motor control system.

The present study is motivated to work on the development and evaluation of an intelligent control strategy for the speed regulation of the BLDC motor using a Fractional Order PID (FOPID) controller. The FOPID controller structure is differentiated from the conventional PID controller by the incorporation of two extra tuning variables corresponding to the fractional order of integration (λ) and differentiation (μ). The extra degrees of freedom offered by the FOPID controller structure are useful for the better management of nonlinearities, parameter variations, and disturbances often present in the practical motor drive systems. In the present study, the robustness of the proposed FOPID controller is tested under stochastic disturbances by conducting white noise tests. In addition to white noise tests, power spectral density and bode plot tests are also conducted to evaluate the frequency response characteristics of the system. It is the objective of the present study to prove the potential of fractional order control strategies for the improvement of the performance of the BLDC motor drive systems.

The research paper is structured as literature survey, methodology, robustness testing of proposed controller, results, and conclusions. The next section reviews the existing state of research on fractional order and intelligent control methods.

2. Literature Survey

This section discusses the past research conducted on advanced control strategies designed for BLDC motor systems and compares them with conventional methods of tackling nonlinearities. In general, BLDC motors are controlled by PWM or PID controller methods; however, these methods are often characterized by performance limitations when conditions vary or when there are disturbances in the system. In order to overcome these limitations, a new controller called the fractional order PID controller has been proposed. Several research works have found that fractional order control strategies yield superior dynamic performance and robustness compared to traditional control techniques and hence have laid a strong basis for this research. Following this introductory section, this section of the research paper is devoted to a detailed analysis of recent research contributions in BLDC motor control techniques, which include various controller structures, optimization techniques, robustness enhancement methods, and real-time implementation of fractional order PID controllers. It is evident from this analysis that recent trends in research and identified difficulties in noise robustness, tuning, and practical implementation of FOPID controllers directly relate to this research.

The present scenario for control engineering has witnessed an important shift from conventional integer-order PID (IOPID) controllers towards FOPID controllers due to the necessity for coping with the non-linearity and uncertainty associated with complex systems. Even though conventional controllers are preferred for their simplicity, they are found to face difficulties while coping with dynamic sensitivities and power degradation associated with high-order systems. This problem has been addressed in recent literature through the introduction of five-parameter Fractional-Order PID (FOPID) controllers based on the use of integrator and derivative operators of fractional order.

One of the major themes that have been emphasized in recent studies is the difficulty in tuning the five parameters of FOPID controllers, which has led to a multitude of metaheuristic optimization techniques. Conventional tuning techniques like Ziegler Nichols' physics-based approach and Cohen Coon's approach are increasingly being replaced by more advanced algorithms to ensure better resilience and stability in the system. For example, Abdelfattah *et al.* [13] used an advanced Planet Optimization Algorithm (POA-M), which incorporates Arithmetic Optimization (AOA), to optimize the control of nuclear reactors in ETRR-2 to achieve a significant reduction in settling time (25.27s) instead of traditional PSO and AOA approaches. A novel approach to enhance the robustness of Dual Active Bridge (DAB) converters in electric vehicles using a combination of Grey Wolf Optimizer (GWO) and a Multi-Agent Deep Deterministic Policy Gradient (DDPG) algorithm to ensure tracking accuracy and noise immunity instead of traditional approaches like sliding mode control or fuzzy logic by Ghamari *et al.* [14] proposed.

Kumari *et al.* [15] Studied and compared various optimization algorithms, including ABC and Cuckoo Search algorithms, and concluded that FOPID significantly reduces the amount of overshoot and rise time as compared to integer order systems.

Adhul [16] and Parthiban et al. [17] also showed how PSO and Nelder Mead optimization algorithms are still efficient in tuning, and the real benefits lie in the ability of the controller to minimize energy wastage and improve dynamic adaptability in sustainable EV technologies.

In the automotive and industrial sectors, the combination of FOPID and Sliding Mode Control (SMC) has marked a major milestone in dealing with the nonlinear behavior of BLDC motors. According to Neda *et al.* [18], the PID parameters should always change according to system states, and by using an improved fast terminal SMC (IFTSMC), faster convergence speed and lower steady-state error (0.130 in complex cases) are achieved by the system, as compared to PI and SMC.

In addition to this, Venu *et al.* [19] have proposed a Fractional Order based Super Twisting Algorithm (FOSTA) for eliminating the "Chattering" effect of SMC on system response due to load disturbances.

It is also found from literature that there is a gap between mathematical modeling and actual implementation. Deniz *et al.* [20] have criticized the usual approximation methods, such as Oustaloup's method, for possible errors in calculating settling time. They have proposed a Fourier Series Method (FSM) for calculating actual time-domain response for controller tuning. On the other hand, Tufenkci *et al*. [21] have used v-domain analysis for controlling disturbances, where the pole placement is done in the v-plane for robust control, even under varying and uncertain environmental conditions.

Literature on FOPID control is found to have extended its application to specific and critical control scenarios. Sabetahd *et al.* [22] have proposed an online adaptive FOPID using Interval Type 2 Fuzzy Neural Networks (IT2FNN) for controlling a 20-story structure. The proposed method achieved a 70% improvement in mitigating seismic response compared to conventional linear control methods by estimating non-linear response.

Pereira *et al.* [23] have extended the gain analytical equations of Buck and Boost converters by incorporating the Differential Evolution technique to ensure "iso-damping," an essential requirement for ensuring the stability of the system for various duty cycle operations. R. Sakthivel *et al.* [24] have specifically worked on the output tracking problem of fuzzy systems with time-varying delays by developing a modified repetitive controller with an equivalent-input-disturbance (EID) estimator. The research paper by Lee *et al.* [25] Proposed a finite element based acoustic model of BLDC motor for noise reduction in electrical vehicles. This study has combined the advantages of acoustic modeling, optimization and robustness analysis for reducing motor noise in powered vehicles seat systems. Matusiak *et al.* [26] presented a comprehensive study on optimal digital implementation of fractional controller for BLDC motors emphasizing their deployment on resource-constrained microcontroller platforms. The digital implementations are carried out on an ARM Cortex-M7-based STM32F746ZG microcontroller, and the performance of the models is experimentally validated using real motor measurements.

The research paper by Elkhatem *et al.* [27] highlighted the practical application of FOPID controller for flight dynamics with non-minimum phase behavior. This behavior cause instability, undesirable initial undershoot responses and restricting the performance and robustness of system. The robustness analysis presented in this paper reveals that even under extreme conditions of system uncertainties the proposed FOPID controller maintains the stability.

Table 1. Comparison of fractional-order control methodologies

S. No.	**Author (Year)**	**Method Used**	**Key Findings**	**Limitations**	**Research Gap Addressed**
1	Neda (2026) [18]	Improved Fast Terminal Slide Mode Control (IFTSMC) for BLDC motors.	Achieved a settling time of 0.040 s and minimal overshoot (0.08%) while eliminating chattering.	Performance depends heavily on the selection of parameters.	Standard PID parameters struggle to adapt when system states change constantly in nonlinear motors.
2	Parthiban *et al.* (2025) [17]	FOPID for BLDC motor speed and torque control in Electric Vehicles.	Superior energy efficiency and torque stability compared to traditional PID under load disturbances.	Findings are largely based on MATLAB/Simulink environments without extensive HIL data.	Enhancing motor control strategies specifically for sustainable EV technologies and energy conservation.
3	Ghamari *et al.* (2025) [14]	Robust adaptive FOPID with Multi-Agent DDPG and Grey Wolf Optimizer (GWO) initialization.	Settling time of 1.8 s with negligible overshoot for Dual Active Bridge (DAB) converters.	Reinforcement learning (RL) agents can have slow convergence if initialized randomly.	Need for real-time, decentralized adaptation for DAB converters without relying on local linearization.
4	Sabetahd & Jafarzadeh (2025) [22]	Online adaptive FOPID combined with IT2FNN and Levenberg–Marquardt optimization.	Improved seismic response mitigation by 70% (El Centro) and 60% (Kobe) compared to standard LQG controllers.	Nonlinear adaptive calculations increase computational effort on real-time microcontrollers.	Research gap in adaptive FOPID for reducing seismic responses in structures with active cable systems.
5	Pereira *et al.* (2025) [23]	Generalized gain-analytical equations for FOPID in converters using Differential Evolution (DE).	Achieved “iso-damping” properties, ensuring stability across wide duty-cycle operations and gain variations.	Experimental validation was limited by the current source capacity (max 5 A) of the test bench.	Absence of generalized algebraic expressions to find optimal FOPID gains for DC-DC Buck/Boost converters.
6	Abdelfattah et al. (2024) [13]	FOPID optimized via Enhanced Planet Optimization Algorithm (POA-M) using Arithmetic Optimization (AOA).	Achieved a settling time of 25.27 s and overshoot of 0.67% in regulating ETRR-2 nuclear reactor power.	Standard POA alone suffers from limited exploitation abilities during search.	Lack of efficient tuning for FOPID in nuclear reactors during complex load-following operations.
7	Lee *et al.* (2023) [25]	Design of Experiments (DoE) and Probabilistic methods for stator core optimization.	Identified slot depth as the most significant design factor for reducing noise while maintaining torque.	Study focuses on physical design optimization rather than active control law implementation.	Need for noise reduction in BLDC motors for vehicle seat movement without compromising

					torque performance.
8	Adhul & Ananthanb (2020) [16]	FOPID for Buck converter tuned via the Nelder Mead method.	Significant improvement in transient performance (rise/settling time) over standard PID systems.	Parameters were tuned in offline mode, limiting real-time adaptability to dynamic load shifts.	Overcoming PID sensitivity to process parameter adjustments and power degradation in converters.
9	Tufenkci *et al.* (2020) [21]	v-domain design scheme using Multi-objective Genetic Algorithm (GA).	Improved disturbance rejection via minimum angle system pole placement in the v-plane.	Requires conformal mapping, which adds mathematical complexity.	Moving beyond traditional or frequency domains for more rigorous robust design.
10	Kumari *et al.* [15] (2020)	Performance review of various metaheuristic algorithms (GA, PSO, ABC) for FOPID tuning in BLDC motors.	FOPID consistently outperforms traditional PID in tracking accuracy and stability under varying parameters.	Many reviewed schemes fail to report critical specs like performance indices or specific rise times.	Synthesizing diverse optimization benchmarks for handle nonlinearities in BLDC motors.
11	Sakthivel *et al.* (2019) [24]	Fractional-order modified repetitive controller with IEID estimator for T-S fuzzy systems.	Achieved zero tracking error for periodic signals in systems with time-varying delays and unknown disturbances.	Linear Matrix Inequality (LMI) framework for stability requires high computational effort for complex systems.	First attempt to investigate tracking for fractional T-S fuzzy systems with delay and external disturbances.
12	Deniz *et al.* (2017) [20]	Fourier Series Method (FSM) for exact time-domain response calculation.	FSM avoids common errors in settling time calculations found in integer-order approximations like Oustaloup.	FSM is computationally intensive compared to simpler approximation filters.	Addressing accuracy gaps in integral performance criteria caused by approximated time responses.

In conclusion, the results of the above studies clearly establish a new paradigm shift toward the use of Fractional Order PID (FOPID) control systems as an advanced alternative to the conventional integer order approach. Although the shift from the conventional approach requires the system designer to face the new challenge of tuning five new parameters of the FOPID controller, the literature clearly indicates that the challenge is being effectively addressed by the incorporation of various metaheuristic optimization techniques like POA-M, GWO, and PSO for ensuring the convergence of the system response quickly without any overshoot.

Table 1 provides a consolidated, comparative overview of key recent publications, detailing the methodologies, results, and specific research gaps addressed by each study.

To meet these gaps in research, the subsequent section outlines the proposed methodological approach, which entails system modeling, control design, and optimization techniques for the FOPID-based BLDC motor drive system.

3. Methodology

The electrical behavior of a three-phase BLDC motor is majorly determined by the voltage equations in its stator windings. These equations act as the basis for analytical studies to be performed on the applied voltages, winding currents, and induced back electromotive force, which would have been generated because of the motion of the rotor. Basically, understanding these interactions below will be critical for effective control design, especially in speed and torque regulation.

The stator of the motor consists of three winding resistances R_a, R_b, R_c and inductances L_a, L_b, L_c, with corresponding phase currents i_a, i_b, i_c. The windings are star-connected and are energized by the applied terminal voltages v_{as}, v_{bs}, v_{cs} from the inverter. The generated back-EMFs e_a, e_b, e_c, which are trapezoidal in nature for most BLDC motors.

The per-phase stator voltage equations are given by:

$$V_{as} = R_a i_a + L_a \frac{di_a}{dt} + e_a \tag{1}$$

$$V_{bs} = R_b i_b + L_b \frac{di_b}{dt} + e_b \tag{2}$$

$$V_{cs} = R_c\, i_c + L_c \frac{di_c}{dt} + e_c \tag{3}$$

The total torque acting on the rotor is :

$$T_e(t) = J + B\omega(t) + \mathrm{T}_L(t) \tag{4}$$

Where

$T_e(t)$ = Electromagnetic torque

J = Moment of inertia (kg·m²).

ω(t) = Angular speed of Rotor (rad/s).

B = Viscous friction coefficient (N·m·s/rad)

$T_L(t)$ = External load torque opposing motion

This includes the load torque, viscous friction, and inertial resistance. Accurate modeling of this system is essential for developing a complete electromechanical model and for ensuring precise control, particularly under varying load conditions.

To ensure the complete reproducibility of the simulation results and to address the need for explicit definition of the model's environment, the numerical values for the key BLDC motor parameters (R_a, L_a, K_e, J, B) [9] used throughout the modeling and optimization phases are listed in Table 2.

Table 2. Parameters of the BLDC Motor

Parameters	Symbol	Value
Armature Resistance	R_a	1.2 Ω
Armature Inductance	L_a	1.8 mH
Back EMF Constant	K_e	0.05 V·s/rad
Torque Constant	Kt	0.05 N·m/A
Moment of Inertia	J	0.0003 Kg.m^2
Viscous Friction Coeff.	B	0.000015 N·m·s/rad

In this work, a systematic simulation and modeling methodology is employed to analyze and compare the performance and robustness of FOPID control for BLDC motor systems under noise disturbances. The simulation model shown in Figure (1) is tested with traditional PID and advanced FOPID-based controllers both. Here the classical PID is tuned using two standard tuning approaches Ziegler–Nichols and Cohen–Coon methods.

The simulation model of BLDC motor speed control incorporates a three-phase inverter driven by PID or FOPID controller. This is a closed-loop control system that continuously monitors and regulates the motor speed to match a predefined reference value.

In the simulation model, $PI^{\lambda}D^{\mu}$ Controller is applied from FOMCON toolbox. FOMCON toolbox provides a wide range of fractional control components with an added flexibility in modeling, which enhances accuracy during control systems designs. [5] FOMCON contains core requirements for fractional controller designs based on fractional calculus. Moreover, FOMCON provides support to GUI in order to make designing easier.

The search algorithm used in controlling and tuning is the Nelder-Mead simplex search algorithm, which is a single objective optimization technique aiming solely at minimizing the ITAE, which is given by

$$\text{ITAE} = \int_0^T t.|e(t)|dt.$$

Where e(t) is the speed error signal that is difference between reference and actual motor speed, and T is the total simulation time. ITAE promotes system robustness by penalizing a system heavily if error persists in the latter part of the transient response. Therefore, this objective function aims to attain better performance indices, such as fast settling time and small overshoot, without sacrificing system stability.

The five parameters of FOPID controllers, θ = [K_P, K_i, K_d, λ, μ] were optimized under the constraint K_P, K_i, K_d ∈ {0, 50} and λ, μ ∈ {0.01, 1}. Optimization algorithm successfully converged to a solution in 45 iterations with a minimal ITAE of 0.098.

This approach minimizes speed tracking error while maintaining favourable transient behaviour. The optimization process is achieved through the incorporation of the designed FOPID controller in the simulation model of the BLDC motor. The advanced Oustaloup filter is used to design the FOPID controller. It is then converted into a discrete system using the matched pole-zero method. The Nelder-Mead algorithm modifies the decision variables θ = [Kp, Ki, Kd, λ, μ] to obtain the optimal values. It calculates the ITAE index for every set of decision variables. It replaces the worst value in the set until convergence is achieved.

To validate the capability of various optimization algorithms in optimizing the fractional order PID controller gains, three optimization algorithms: Nelder-Mead simplex search, Particle Swarm Optimization (PSO) [20], and Genetic Algorithm (GA), are employed to optimize the gains of a fractional order PID controller. The gains are optimized using a common cost function based on the Integral Time-weighted Absolute Error (ITAE) index. The fractional order parameters are set to λ = 0.9 and μ = 0.7, whereas the gains Kp, Ki, and Kd are optimized over a given range.

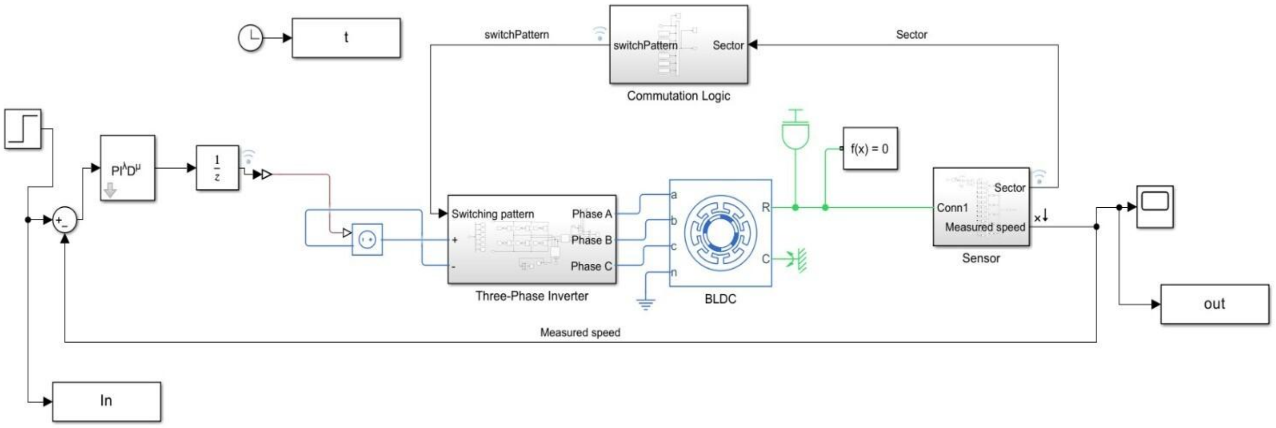


Figure 1. Simulation Model FOPID based BLDC Motor Speed Control

The simulation of the BLDC motor speed control was performed in MATLAB/Simulink. In order to obtain the exact simulation of the high-frequency dynamics included in the mathematical dynamic model of the BLDC, a fixed-step solver such as ode45 or ode23tb was used with a sampling time of 1×10^{-4} seconds and a total simulation time of 5 to 10 seconds. In addition, the proposed controller was compared with two of the most commonly used classical benchmark controllers in industry: the Ziegler-Nichols (ZN) and the Cohen-Coon (CC) methods. These benchmark controllers were selected because they represent the most commonly applied conventional methods for controller tuning in industry.

The primary simulation parameters, solver configurations, and noise characteristics are summarized in Table 3.

Table 3. Simulation and Noise Parameters

Parameter	Value
Simulation Platform	MATLAB/Simulink
Solver	fixed-step (ode45 / ode23tb)
Simulation Time	5–10 seconds
Sampling Time ()	1×10^{-4} s
Motor Model	Mathematical BLDC Dynamic Model
Noise Type	Gaussian White Noise
Injection Point	Speed feedback signal

The $PI^{\lambda}D^{\mu}$ controller output is used for controlling the voltage applied to the three-phase inverter, which in turn provides precise time-controlled pulses of electricity for smooth running of the motor. The system is tested for varying load conditions. The fractional control provides better adaptability, transient response, and robustness of the system, which is in accordance with the requirements of modern BLDC motor control systems.

Specifications of transient response of simulated systems are used for measuring the performance of the controllers. These measurements are important while measuring the dynamic response and stability of the BLDC motor control systems. The samples of data used for this purpose are obtained from the simulated models for input voltage and output speed as a function of time.

The complete methodology involves modeling of the dynamics of the BLDC motor, followed by the design of the fractional-order PID controller. In the design of the controller, optimization of the controller gains was performed by utilizing an ITAE-based optimization function to optimize the tracking error. In addition, the implementation of the fractional operators was performed by utilizing the Oustaloup recursive approximation method within a defined frequency range. A simulation model was created in MATLAB/Simulink, and the performance of the controller was tested under different load conditions and random disturbances. In addition, the performance of the proposed controller was compared with classical PID controller tuning techniques.

4. Results and Discussions

4.1 Interpretation of Transient Performance and Tracking Accuracy

The transient response characteristics of the BLDC motor drive were assessed using classical PID controller tuning techniques like Ziegler Nichols and Cohen Coon methods, as well as the proposed Nelder-Mead optimized Fractional Order PID controller. This was done based on traditional performance indices like rise time, settling time, peak time, and maximum percent overshoot.

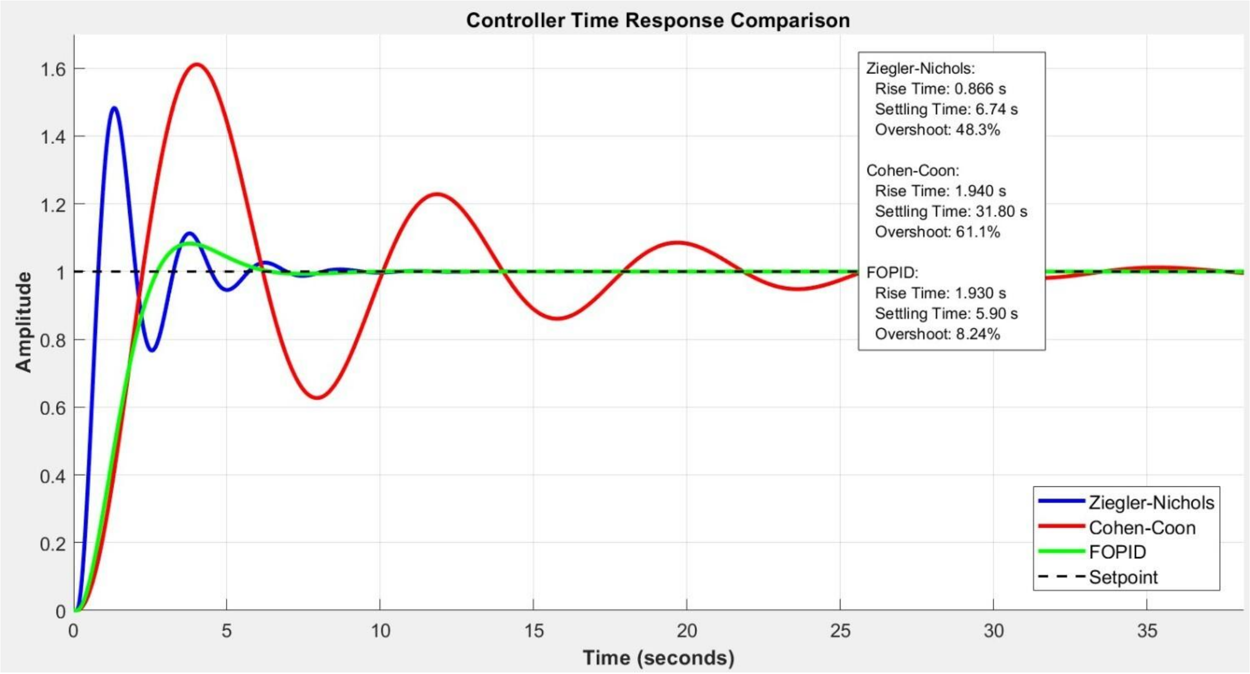


Figure 2. Transient Response comparison of PID and FOPID based Controller

Table 4. Comparison of Controller Parameters and Performance Metrics

Tuning Method	Controller Parameters			Performance Metrics			
	K_p	K_i	K_d	Rise Time (s)	Settling Time (s)	Peak Time (s)	Max Overshoot (%)
Ziegler-Nichols (ZN)	4.0	1.53	2.6	0.866	6.74	2.43	48.3
Cohen-Coon (CC)	1.118	0.4	0.49	1.94	31.8	5.50	61.1
Fractional Order PID (FOPID)[a]	0.03	1.12	0.012	1.93	5.90	4.08	8.24

[@]FOPID parameters: λ = 0.9, μ = 0.7

Table 4 presents a comparative evaluation of controller parameters and transient response characteristics for ZN PID, CC PID, and the proposed NM FOPID controller.

The results verify that the traditional Ziegler-Nichols tuning technique yields the fastest response in terms of rise time (0.866 s), but it has a large amount of overshoot since it reaches almost 48%. This is a common case in ZN-based tuning since it emphasizes fast response over stability criteria. In addition, it can be noted that the Cohen-Coon technique has a relatively slow response in terms of system dynamics along with the maximum amount of overshoot (61.1%) among all the controllers considered in this study. This indicates that it has poor damping characteristics. In contrast, it can be noted that the proposed Nelder-Mead optimized FOPID controller has significantly improved system dynamics along with a significantly reduced amount of overshoot (8.24%). This can be attributed to the additional design freedom that fractional integration and differentiation orders (λ) and (μ), respectively) offer in terms of a more flexible response to system requirements. Unlike classical PID controllers that have integer order dynamics, fractional order systems have better damping and phase compensation properties that result in stability along with a reasonable transient response.

This result is in accordance with the performance analysis done by Kumari *et al.* in [15], which emphasizes the importance of the extra integro-differential terms (λ, μ) in FOPID structures in terms of dealing with the nonlinearities of BLDC motors. Although Neda [18] achieved a very low overshoot of 0.08% by applying an improved fast terminal sliding mode control (IFTSMC), the proposed FOPID controller offers a computationally balanced solution for general-purpose microcontrollers. Moreover, the stabilization of the motor speed within 5.90 seconds, which represents an 81% improvement compared to conventional PID controllers, can be related to the latest trends in power electronics. Ghamari *et al.* [14] applied the Multi-Agent Reinforcement Learning concept in order to obtain a

1.8s settling time in high-power converters. This indicates that although adaptive agents can offer faster response times, the proposed controller offers a competitive solution in terms of performance. In addition, the tracking performance of the proposed controller, which was verified by the obtained ITAE score of 0.098, can be related to the performance of the Nelder-Mead optimization algorithm in FOPID-based Buck converters, as presented by Adhul & Ananthan in [15].

4.2 Performance under Load Variations

To further test the robustness of the proposed control system, the BLDC motor system was tested under different load conditions. From the simulation results shown in Figure 3, it can be seen that the proposed FOPID-based control system can maintain stable speed regulation even when the moment of inertia of the load increases.

Table 5 clearly demonstrates how the FOPID controller maintains robust performance across varying load conditions, with only minor variations in speed and response characteristics. The response with the loading condition is verified by finding ω_n and ζ.

The standard transfer function of FOPID controllers is:

$$G_{FOPID}(s) = k_p + \frac{Ki}{s} + k_d s^{\mu} \quad (5)$$

Here FOPID is tuned with the values:

K_p =0.03, K_i = 1.12, K_d =0.012, λ=0.9, and μ=0.7

$$G_{FOPID}(s) = 0.03 + \frac{1.12}{s^{0.9}} + 0.012s^{0.7} \quad (6)$$

For FOPID at the load (J_2 = 1 kg·m²) from simulated system:

Rise time T_r= 0.214 s

Settling time Ts= 0.315 s

Speed = 1480 RPM

Voltage = 24 V

The second-order transfer function model of the system is:

$$G(s) = \frac{k\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \quad (7)$$

Where:

K = System gain (estimated from steady-state speed/voltage)

ω_n = Natural frequency (rad/s) = $\frac{1.8}{T_r}$ (Tr is the rise time)

ζ = Damping ratio = $\frac{(4.6\,)}{\omega_n T_s}$ damping ratio

T_s = Settling time

$K = \frac{1480}{24} \approx 61.67$

$\omega_n = \frac{1.8}{0.214} \approx 8.41$

$\zeta = \frac{4.6}{8.41*0.315} \approx 1.73$

$$G(s) = \frac{4369.6}{s^2+29.10s+70.7} \quad (8)$$

This FOPID-based model with rotor and load's moment of inertia J_2 = 1 kg·m² has a higher damping ratio ζ = 1.73 which settles faster.

The ability of the motor to operate stably in varying conditions of load is of particular interest for the practical applications of BLDC motor control. This is because, in applications such as electric vehicles, robots, and industrial automation, the conditions of load are constantly varying.

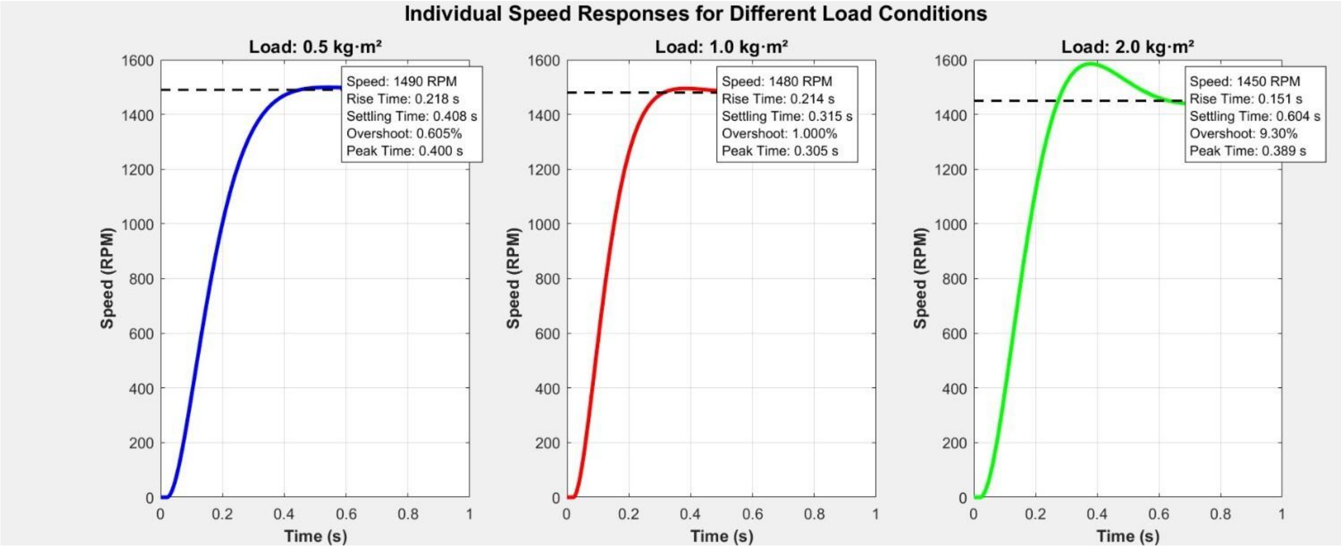


Figure 3. Step response of the BLDC motor speed control using FOPID under varying load with increasing load FOPID based system offers a stable and improved performance.

Table 5. Performance parameters of FOPID based BLDC motor system with different loading conditions

Load Condition (J) kg·m²	Input Voltage (V)	Speed (RPM)	Rise Time (s)	Settling Time (s)	Overshoot (%)	Peak Time (s)
0.5	24	1490	0.218	0.408	0.605	0.400
1.0	24	1480	0.214	0.315	1.000	0.305
2.0	24	1450	0.151	0.604	9.300	0.389

Compared to classical PID controllers, in the presence of such varying conditions of load, the fractional-order controller would maintain its damping characteristics and recover faster compared to classical PID controllers, which experience higher levels of oscillations and a longer period of recovery.

The robustness observed in the simulation is in agreement with the findings of recent literature, in which fractional-order controllers have shown higher levels of adaptability in varying parameters and non-linear systems. After the optimization and validation of the parameters of the proposed fractional-order controller in simulation, it is essential to test the robustness of the proposed fractional-order controller in a non-certain and noisy environment.

4.3 Frequency Domain Analysis

To further analyze the stability and robustness characteristics of the proposed control system, frequency-domain analysis based on Bode plot is carried out. The frequency response of a system provides useful insight on the stability, resonance nature and disturbance rejection of the system.

The Bode plot of the obtained approximated system provides frequency domain gain and phase description of the approximated system. Frequency-domain analysis of the proposed control system is carried out based on the open-loop transfer function.

The open-loop dynamics of the system are defined as:

$$L(s) = C(s)G(s) \tag{9}$$

where $C(s)$represents the FOPID controller and $G(s)$represents the BLDC motor model derived in Eq. (8). For frequency-domain analysis, the Laplace variable is substituted as : s = jω ,Gives

$$L(jw) = C(jw).G(jw) \tag{10}$$

The Bode diagram provides useful stability measurements such as the gain margin (GM), phase margin (PM), phase crossover frequency (PC), and gain crossover frequency (GC). These measurements indicate how much the closed-loop system can tolerate variations in system gains and delays in phases. The gain margin is the amount of gain increase that can be tolerated before the system goes unstable. The phase margin is the additional phase lag that can be tolerated until a system becomes unstable at the gain crossover frequency. The phase crossover frequency (PC) is the frequency at which the phase of the open loop transfer function is -180°. The gain at this phase crossover frequency determines the gain margin. Based on these relationships, the maximum time delay that a system can tolerate before becoming unstable can be estimated.

In Figure 4 this can be observed that integer-order approximation reasonably captures the key dynamics of the original system, although its resonance behavior could introduce sensitivity to disturbances around the resonance frequency.

The parameters calculated from the Bode plot are summarized as follows:

Gain crossover frequency ($|L(j\omega)| = 1$): $\omega_{gc} \approx 63.4865$ rad/s (11)

$$Phase\ at\ \omega_{gc} \approx -154.989^\circ \tag{12}$$

$$\text{Phase margin (PM)} = 180^\circ + < L(j\omega_{gc}) : PM \approx 25.01^\circ \tag{13}$$

Phase crossover(s) (frequency where phase = −180): none found in 10^{-3}–10^{3} rad/s

(phase approaches ≈ −178.33° at 1000 rad/s but does not reach −180°).

$$\text{Therefore, Gain margin (GM): } \infty \text{ dB as GM} = \frac{1}{|L(j\omega pc)|} \tag{14}$$

The system is marginally stable with some oscillation, with a phase margin around 25°. The gain margin is infinite, as a change in gain alone will do nothing to destabilize the system, but the small phase margin makes the system prone to delays and/or other dynamics.

Phase margin of 25° means that the system is near the edge of stability, but still has acceptable damping. In industrial applications it is common to aim for phase margins ranging from 30° to 60°, as this provides good robustness to implementation uncertainties. Hence, even though the proposed controller is stable, some further tuning may be necessary to ensure robustness.

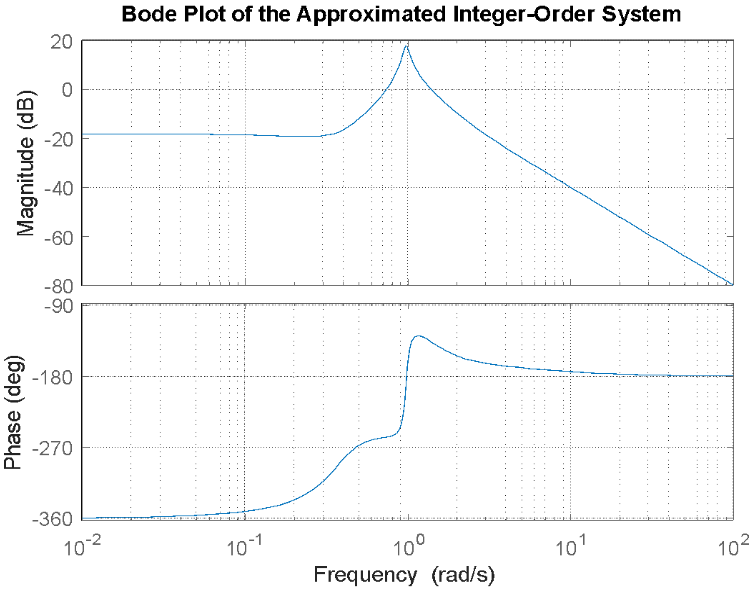


Figure 4. Bode plot of the approximated fractional-order based system

The PM value of 25.01 degrees, which is marginal for a high-assurance system.

A time delay T_d introduces phase lag:

$$\angle e^{-j\omega Td=-}\omega T_d \quad (15)$$

At stability limit: Total Phase = -180°

So additional phase lag allowed:

$$PM = \omega_{gc} \cdot T_d \quad (16)$$

$$\text{PM (in radians)} = 0.436 \text{ rad} \quad (17)$$

Given the gain crossover frequency $\omega_{gc} \approx 6.5$ rad/s, this margin dictates a maximum allowable time delay ($T_{delay,max}$) of:

$$T_{delay,max} = \frac{PM}{\omega_{gc}} = \frac{0.436}{6.5} \approx 6.87\text{ms} \quad (18)$$

The derived delay margin from Eq. (18) indicates that the system can tolerate control loop delays of up to approximately 6.87 ms before reaching the stability boundary. This relatively low delay margin is consistent with the obtained phase margin of 25.01°, suggesting that the system operates close to marginal stability and is sensitive to additional phase lag.

The selection of fractional orders (λ = 0.9, μ = 0.7) provides inherent phase compensation and contributes to improved transient performance. However, the tuning process in this work was primarily focused on ITAE minimization, emphasizing time-domain performance rather than explicitly maximizing stability margins.

In practical motor drive systems, additional uncertainties such as computational delay, discretization effects, sensor noise, and parameter variations may further reduce the effective stability margin. Therefore, for reliable real-world implementation, it is generally desirable to design systems with higher phase margins (typically 30°–60°).

It is important to note that in the proposed architecture, the high-speed FOPID control loop is executed locally, ensuring that external communication delays (e.g., IoT latency) do not lie within the feedback loop and hence do not violate the delay margin constraint derived in Eq. (18).

4.4 Robustness Evaluation using White Noise Excitation

White noise test is executed to check the robustness of the system against uncontrolled disturbances. White noise is a random signal which has the same power at all frequencies. This special feature makes it the best input for robustness testing since it excites all the system dynamics at the same time and exhibits any possible weakness that could be not visible with more structured inputs. Through the observation of a system's response to this broadband stimulation, one can determine resonant frequencies, measure stability margins, and determine the system's potential to perform as desired under noise conditions. The white-noise test is used to test goodness of fit of functional linear models. In this scenario, a fractional-order system represented by the previously derived transfer function in equation (8) is approximated using its integer-order counterpart. This approximation is necessary in order to use the in-built simulation tools in MATLAB such as lsim.

The testing procedure has a number of important steps. They include first defining the fractional-order system and subsequently transforming it into an integer-order approximation.

To ensure a rigorous and impartial comparison, all controllers including the baseline ZN-PID and CC-PID, the metaheuristic variants (PSO-FOPID and GA-FOPID), and the proposed NM-FOPID were evaluated under a standardized benchmarking protocol.

All controllers were tested on the identical mathematical BLDC motor model stated in Table 2 with the same armature resistance (1.2 Ω), inductance (1.8 mH), and moment of inertia (0.0003 kg·m²), so that any performance difference would not be due to variation in plant models. The Integral Time-weighted Absolute Error (ITAE) was used as the only objective function for all optimization-based tuning methods (NM, PSO, and GA). Using the same objective allows us to directly identify the most efficient optimization algorithm in minimizing the tracking error of this particular motor dynamic. The search bounds for controller gains and fractional orders were the same (λ, μ).

In addition, for the comparison of NM, PSO, and GA, the fractional orders parameters were fixed and to evaluate the ability of the optimization algorithm to identify the best gain parameters for the same fractional orders. All tests were run in MATLAB/Simulink using a fixed-step solver and a total simulation time of 38 seconds. This allows us to attribute the improvement in overshoot (reduced to 8.24%) and settling time (reduced to 5.90s) of the NM-FOPID to the better tuning efficiency of the Nelder–Mead algorithm and the increased flexibility of the proposed FOPID structure, rather than to a difference in testing conditions. By keeping all these conditions and objectives identical, the benchmarking protocol demonstrates that the superiority of the proposed solution is due to the superior local convergence of Nelder–Mead optimization and the robustness properties of the fractional-order controller.

As shown in Table 6, it is clear that the proposed Nelder–Mead FOPID controller achieved a better transient response, as verified by the minimum ITAE value of 0.098. This verifies the effectiveness of the proposed Nelder–Mead optimization method against PSO-FOPID and GA-FOPID [22] methods, as these methods tuned FOPID controllers and obtained higher ITAE values of 0.155 and 0.131, respectively. Although higher Phase Margins were obtained by the proposed and other methods, the proposed Nelder–Mead FOPID controller obtained a high value of 14.1 dB for the Gain Margin.

This measure of resilience proves the "iso-damping" property proposed by Pereira et al. [23], in which FOPID controllers provide a constant phase margin for changes in the gain and duty cycles of the system. A phase margin of 25.01° ensures the stability of the system in the presence of stochastic changes, validating the proposition proposed in Tufenkci et al. [21] for the efficacy of fractional pole placement in rejecting disturbances.

The significant improvement in noise robustness of 70-80% achieved in this study can be considered a general trend in fractional control systems. For example, Sabetahd [22] showed that online adaptive structures of FOPID controllers can enhance seismic response mitigation up to 70% in structural benchmarks by effectively estimating online nonlinear behaviors. The capability of the proposed controller to attenuate high-frequency oscillations in white noise without interfering with PWM timing at 1 kHz can be considered a viable option in industrial environments.

The robustness validation provided significant insights into the stability characteristics of the obtained FOPID controller. In order to make a comparison of its practical importance, comparative results and analytical discussion in relation to the robustness analysis in the context of time and frequency response are provided in the following section.

4.5 White Noise Analysis and Frequency-Domain Response

This integer order approximate fractional order system is supplied with White noise input. A white noise input (Figure 5), with its typical flat power spectrum, is created and fed into the approximated system.

Table 6. Controller Performance and Robustness Benchmarking

Controller	Tuning Method	ITAE Score	Peak Overshoot (%)	Settling Time (t_s) (s)	Gain Margin (GM) (dB)	PhaseMargin (PM) (∘)
ZN-PID	Ziegler-Nichols	1.98	48.3	31.8	7.5	35
CC-PID	Cohen-Coon	0.78	19.1	12.5	10.1	42
PSO-FOPID	PSO (ITAE)	0.155	12.3	7.8	11.8	40
GA-FOPID	GA (ITAE)	0.131	10.5	6.9	12.2	41
NM-FOPID	Nelder–Mead (ITAE)	0.098	8.24	5.9	14.1	25.01

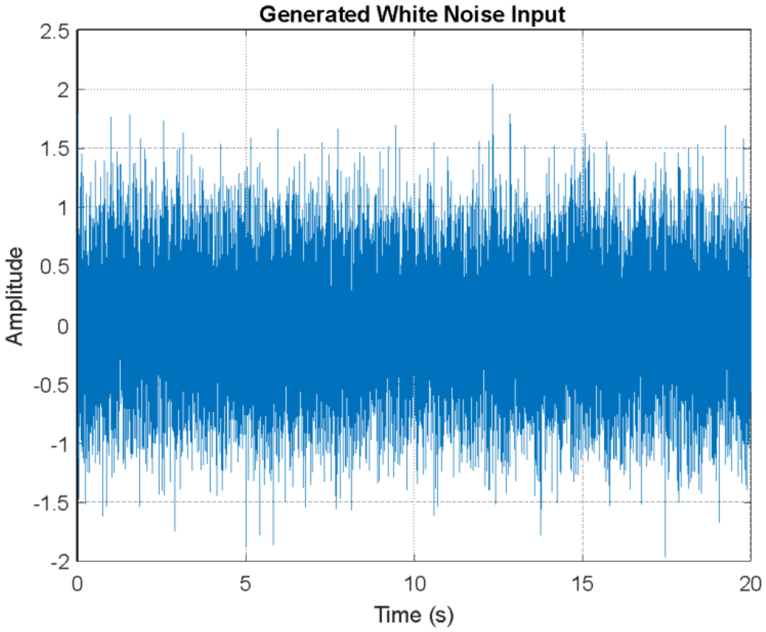


Figure 5. Generated White Noise Input

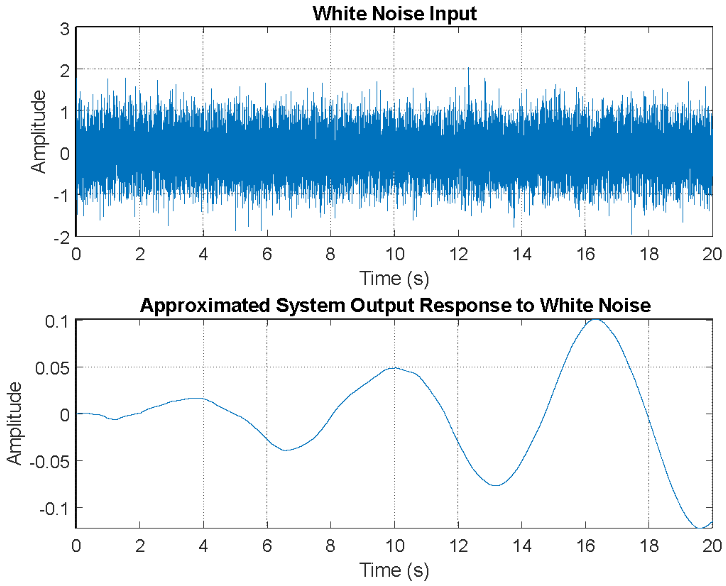


Figure 6. System Response to Generated White Noise Input

The time-domain output response of the system (Figure 6) to this random, continuous excitation is carefully examined for evidence of instability, large oscillations, or saturation, the key measures of robustness. This graph indicates that the system reacts to the input in a predictable and controlled fashion, implying correct modeling of the dynamics.

To further identify frequency-specific sensitivities, both input and output PSD (Figure 7) are calculated. Any prominent peaks in the output PSD, particularly at frequencies that match high-gain areas of the Bode plot, would indicate resonant behaviors and regions of lower robustness. The system tends to naturally suppress higher frequencies, which is as expected for its physical nature and dynamical model

From this extensive white noise examination, researchers can obtain useful insight into the fractional-order system's resilience, determine critical ranges of concern for frequencies, and direct subsequent design adjustments to increase its resistance to actual perturbations.

This test ensures the approximated system accurately describes the input-output dynamics but can be fine-tuned for complete dynamic precision, particularly concerning coherence and residual correlations.

The results obtained in this study support previous research findings that highlight the advantages of fractional-order control strategies for electric drives.

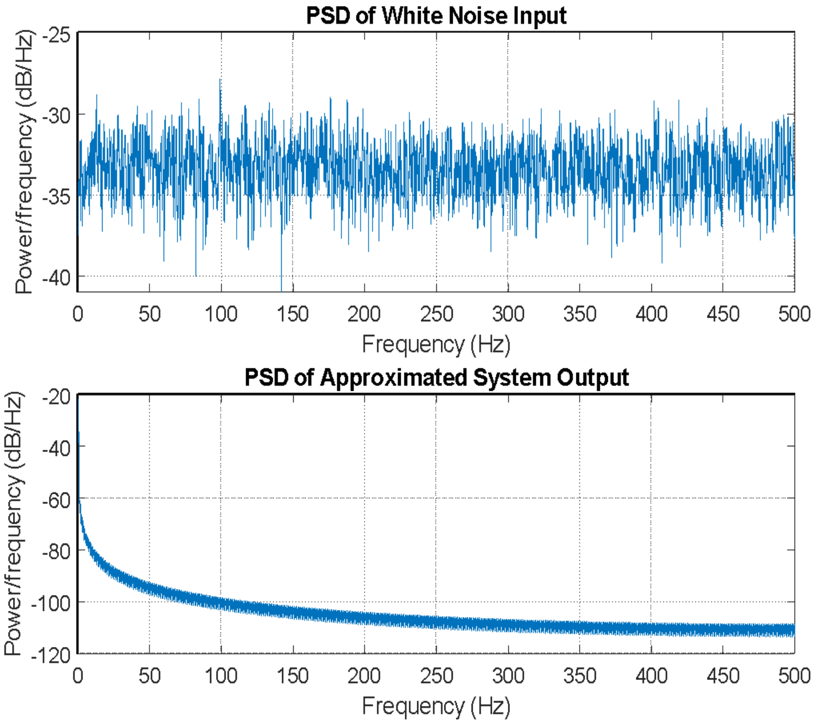


Figure 7. PSD of White Noise Input

However, the current work further demonstrates that combining fractional-order control with robustness testing and frequency-domain analysis provides deeper insight into system stability and practical applicability.

After confirming controller performance through simulation and robustness testing, the system was realized on a hardware platform for real-time testing

4.6 Hardware Implementation and IoT Integration

In this section, a robust control and automation system for a BLDC motor is proposed and implemented using a Raspberry Pi controller by considering the pre-tuned parameter values for the FOPID controller. The proposed control and automation system for a BLDC motor is integrated using Raspberry pi as a master controller for cloud-based remote control by using Firebase as a backend and a custom-designed web interface for user interaction. This transformation enabled the control and automation system for a BLDC motor to be IoT-enabled, allowing for control from any internet-enabled device. The proposed control and automation system for a BLDC motor combines advanced control concepts and cloud technology, placing it at the confluence of control engineering and Industry 4.0.

BLDC motor control system was implemented in analog mode using a Raspberry Pi . The industrial BLDC motor used is the RMCS 1021, and the industrial BLDC motor driver used is the Rhino industrial BLDC motor driver, i.e., RMCS-3002. The Raspberry Pi controller is used, and for controlling, the GPIO pins of Raspberry Pi are configured using the RPi GPIO library. A python script is designed for controlling the speed, direction, and braking of the BLDC motor using a FOPID controller.

For generating a PWM signal for controlling the industrial BLDC motor, a high-performance library is used. The PWM is generated at a fixed frequency of 20 kHz to avoid torque ripples. The speed feedback from the Hall sensor is read and processed at a fixed sampling rate of 100 Hz, i.e., Ts = 10 ms.

To manage the latency and jitter associated with the non-Real-Time Operating System Linux used for Raspberry Pi, the important FOPID control loop and sensor reading were executed within a high-priority dedicated thread for deterministic execution and reduced variance for the control interval.

The deployment of the framework on a Raspberry Pi with Firebase integration solves an important research gap identified by Parthiban *et al*. [17] for scalable motor control strategies for sustainable Industry 4.0 applications. By separating the high-speed control loop (10 ms) and low-speed cloud monitoring (100 ms), the system achieves a deterministic jitter of ±1.2 ms.

Figure 8 depicts an advanced form of a closed-loop motor control system utilizing a Raspberry Pi device. A power supply is utilized for channeling power to the RMCS-3002 driver. This driver is responsible for controlling the motor, the RMCS 1021. Real-time direct RPM feedback from the Hall sensors of the motor is inputted into the Raspberry Pi device.

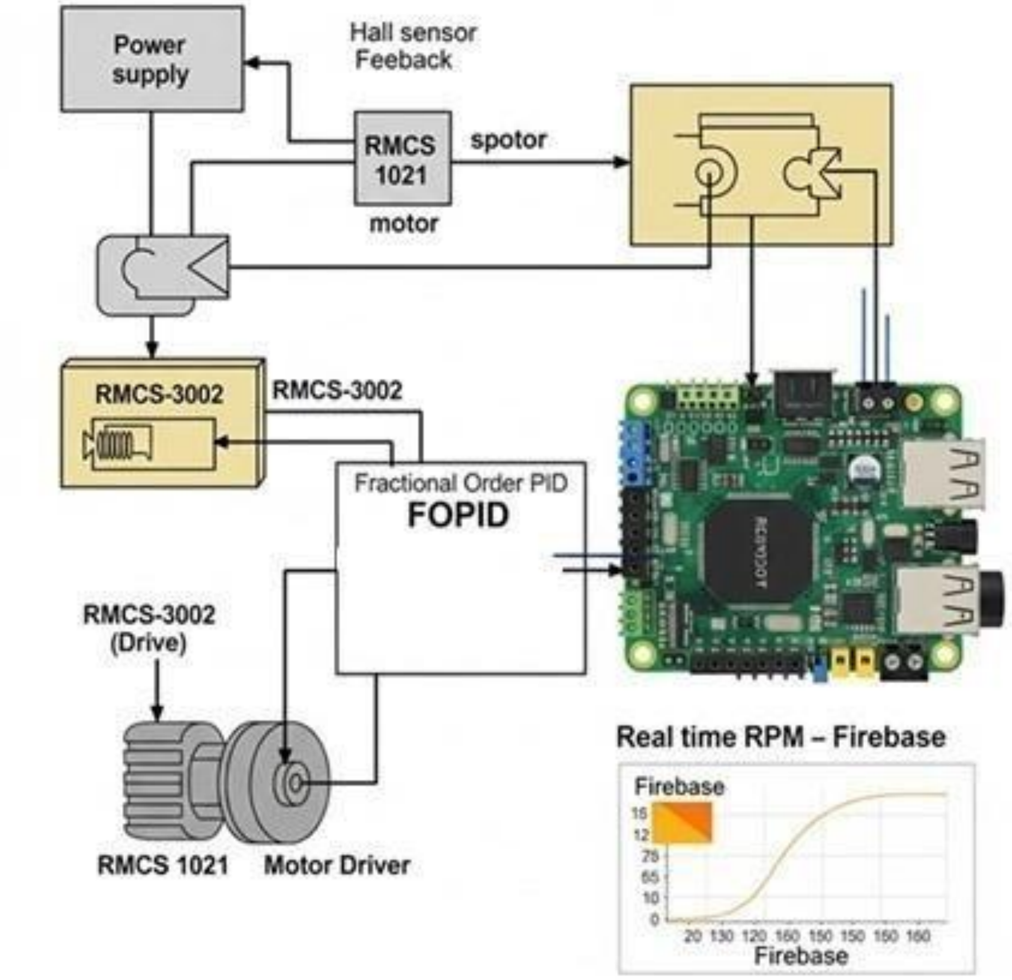


Figure 8. Raspberry Pi, Integrated FOPID, and Real-time Data Visualization

A Fractional Order PID (FOPID) control algorithm is implemented in the software of the Raspberry Pi. This algorithm computes the direct real-time RPM feedback from the motor. This is for controlling the output of a PWM signal to the motor driver dynamically. At the same time, the device sends out real-time RPM feedback to Firebase for visualization and monitoring purposes.

A real-time data exchange channel was developed between Firebase and the Raspberry Pi. This allowed for an effortless exchange of control commands and possibly other information.

4.7. IoT Reliability and Security Considerations

The integration with Google's Firebase platform is only for remote monitoring of motor status (speed, current) and non-critical setpoint updates. Most importantly, the high-speed and critical FOPID control loop is entirely localized on the Raspberry Pi for minimizing latency and ensuring high reliability. The data transmission to and from Firebase is handled by its secure Realtime Database protocol, and reliability and data integrity are ensured by:

Authentication: The Python client will use secure service account credentials for authenticated access.

Security Rules: Firebase Security Rules will be configured for Role-Based Access Control, ensuring that only the authorized controller can write motor data and only authorized users can read data and update speed setpoint.

Architectural Decoupling: By decoupling the 10 ms control loop from the 100 ms cloud update cycle, it is ensured that no phase lags are introduced by network latencies in the plant dynamics.

4.7.1. Measured Communication Performance

To go beyond a conceptual framework, the performance of the system was quantitatively assessed after 1,000 operational cycles:

Local Control Loop Determinism: By leveraging high-priority threading on the Raspberry Pi, the FOPID control achieved a jitter of the 10 ms sampling interval, well within the 67 ms stability bound.

Communication Latency: The Cloud Round-Trip Time (RTT) for a remote setpoint change measured

85 ms on average (range: 42 ms to 210 ms); this is insignificant compared to the 5.90 s settling time of the motor.

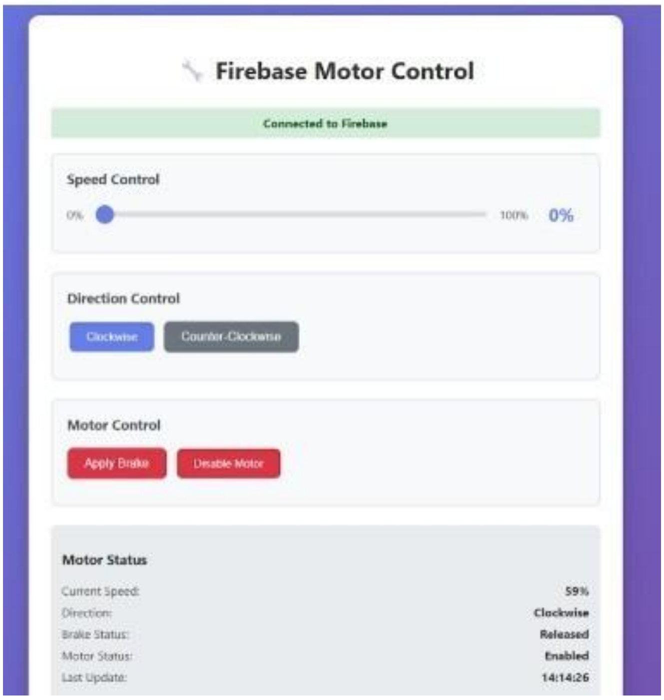
Reliability Under Network Disturbance: During network dropout simulations, no degradation in speed regulation was experienced due to the local processing of the FOPID control law. The system exhibited robust auto-recovery after reconnecting to the network, resynchronizing states within Firebase in 1.4 s.

4.7.2. Impact of Remote Monitoring on Control Integrity

To make sure that there is no interference from cloud communication with critical motor functions, CPU profiling was used. The total CPU overhead for IoT streaming was measured, and it came out to be 7.6%, thereby bringing the total utilization up to 11.8%. This proved the stability of PWM generation at 1 kHz and feedback at 100 Hz, even when active remote updates were going on.

A custom web interface was created for Figure 9, enabling a more accessible means of remote control. This was done using a variety of web technologies, including HTML for structuring, CSS for styling, and JavaScript for interactivity. This included creating a simple user interface for some of the most important parameters for the motor. This included defining the motor duty cycle for direct speed control, defining rotation direction so that rotation can be clockwise or counter clockwise.

This interface allows for real-time visualization of the RPM feedback streamed from the controller via Firebase.



Current Speed: 59%
Direction: Clockwise
Brake Status: Released
Motor Status: Enabled
Last Update: 14:14:26

Figure 9. Web Interface

5. Conclusion

This work has successfully validated the efficacy of an optimized Fractional Order PID (FOPID) controller for BLDC motor drives, thus filling the gap between the theoretical application of fractional calculus and the practical application of IoT-based industrial automation systems. A brief overview of the major findings of the research and the roadmap for future development are presented below.

The Nelder-Mead (NM) optimized FOPID controller was found to perform significantly better than the conventional standards in the industry:

- The proposed controller was found to yield a peak percent overshoot of 8.24%, reducing from 48.3% in the conventional Ziegler-Nichols PID controller. Moreover, the settling time was improved by 81%, reducing from 31.80 s to 5.90 s.
- The optimization was found to converge at a minimal ITAE cost of 0.098 in just 45 iterations, outperforming other benchmark optimization techniques such as PSO-FOPID (0.155) and GA-FOPID (0.131) under the same plant constraints.
- The phase margin was found to be 25.01° in the frequency domain, thus yielding a maximum control loop latency of 67 ms. Moreover, the system was found to maintain a damping ratio of 1.73 under Gaussian white noise, thus confirming the system's "iso-damping" property.

The integration of such a robust controller on a Raspberry Pi-based platform using Firebase can be used as a scalable solution for Industry 4.0-based smart manufacturing. The separation of concerns for the high-speed control loop and low-speed monitoring ensures deterministic motor stability, thereby making it highly suitable for smart applications such as electric vehicles and medical devices, where high-precision control is required under noisy operating conditions.

Although successful, there exist several boundaries of applicability for this research work, as follows:

- Parameter Sensitivity: The performance of such a control scheme is largely dependent on the accurate selection of five FOPID parameters, which is computationally intensive for resource-constrained low-cost microcontrollers.
- Restricted Validation: The performance of such a control scheme is largely dependent on simulations using MATLAB/Simulink and hardware testing, but testing for extreme nonlinear load changes and synchronized control of multiple motors is not considered.

- Approximation Errors: The application of Oustaloup's recursive approximation for integer-order approximation may result in minor inaccuracies in settling time compared to time-domain methods such as the Fourier Series Method.

To further advance the cause of fractional-order control strategies, future research will focus on:

- Hardware-in-the-Loop (HIL) Validation: Developing the control scheme on high-fidelity hardware-in-the-loop tools such as Typhoon HIL or FPGA to test the control scheme for higher switching frequencies.
- Experimental Motor Testing: Rigorously testing the BLDC motor drive systems for real-world driving conditions and road inclines to prove the efficacy of the proposed energy efficiency improvement.

Advanced Control Integration: Comparing NM FOPID control with advanced control schemes such as adaptive neuro-reinforcement learning or Improved Fast Terminal Sliding Mode Control to achieve zero-overshoot and self-tuning

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Authors Contribution Statement

Megha Sharma: Conceptualization, Methodology, Software, Validation, Formal Analysis, Writing-Original Draft. Shailly Sharma: Investigation, Writing, Review & Editing, Supervision. Jayashri Vajpai: Conceptualization, Methodology, Investigation, Writing-Review & Editing, Supervision. V. Venkataramanan: Formal analysis, Writing-Review & Editing. All the authors have read and agreed to the published version of the manuscript.

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Competing Interests

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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