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A Novel Approach to Design and Analyze Fractional Order PID Controller for Speed Control of Brushless DC motor

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ABSTRACT

Brushless direct current motors with conventional Proportional Integral Derivative controllers based on linear control theory are widely used in industries. Brushless motors often require precise speed control for applications such as robotics, electric vehicles and industrial automation. The recent advancement in Fractional order calculus in control theory is also seeking attention of researchers because of certain advantages over conventional controllers. In comparison with conventional control of Brushless direct current motor, Fractional order proportional integral derivative controllers outperform in terms of better dealing with variable time delays, varying plant parameters, nonlinearity and considerable plant noise. This research paper delves into the potential of fractional order proportional integral derivative controllers as a superior alternative. By leveraging the advantages of fractional calculus, Fractional order proportional integral derivative controllers offer enhanced adaptability, robustness, and performance compared to conventional proportional integral derivative controllers.

The paper presents a novel approach to design a fractional order proportional integral derivative controller for control of brushless direct current motor and gives a comprehensive comparative analysis of conventional and fractional order control. Overall, it is noticed that the novelty of Fractional order proportional integral derivative controllers lies in its ability to leverage fractional-order dynamics to achieve improved control performance, enhanced adaptability, and better robustness as compared to traditional proportional integral derivative controllers. The proposed models of Fractional order proportional integral derivative based control of Brushless motors are designed and validated in Simulink environment. The simulation results demonstrate the effectiveness of the fractional order proportional integral derivative controller in achieving precise speed control, improved transient response, and enhanced disturbance rejection under load variations.

Index-words: *Graphical User Interface (GUI), Proportional Integral Derivative (PID) Controller, Fractional Order Proportional Integral derivative (FOPID) Controller, Pulse Width Modulation (PWM), Ziegler Nichols tuned Controller (ZN-tuned Controller).*

Abbreviations	
BLDC Motor	Brushless Direct Current motor
PID Controller	Proportional Integral Derivative Controller
FOPID Controller	Fractional Order Proportional Integral Derivative Controllers
PWM	Pulse Width Modulation
HVAC	Heating Ventilation and Air Conditioning
PMSM	Permanent Magnet Synchronous Motors

I. INTRODUCTION

Brushless Direct Current (BLDC) motors have wide range of applications devices in complex industrial machines. In these motors electrical energy is converted into rotational motion by changing flux through wave shaping. Brushless DC motors offer several advantages over traditional brushed motors, including higher efficiency, lower maintenance requirements, longer lifespan, and improved reliability. These characteristics make brushless motors suitable for various applications, including automotive systems, industrial machinery, robotics, and consumer electronics. The basic construction of a Brushless DC motor includes a stator with coils and a rotor with permanent magnets or electromagnets. When electric current is applied to the coils in the stator, it generates a rotating magnetic field that interacts with the magnetic field produced by the rotor, resulting in motion.

In applications where precise control of speed and torque is necessary, such as in robotics or electric vehicles, Brushless DC motors are often paired with sophisticated control systems, such as Proportional Integral and Derivative (PID) controllers, to achieve optimal performance. The motor speeds can be varied with the help of a suitable conventional controller. This speed variation can be done by applying variable DC voltage using a process known as pulse-width modulation. [1]

The need for speed control in Brushless DC (BLDC) motors arises from the demand for precise and adaptable motor performance across various applications. BLDC motors power a wide range of devices, from industrial machinery to consumer electronics, where maintaining consistent speed and torque is critical. Speed control enables efficient operation, improved energy consumption, and enhanced performance in applications such as electric vehicles, robotics, and Heating Ventilation and Air Conditioning systems. Additionally, it allows for dynamic response to changing loads and environmental conditions, optimizing the motor's functionality and extending its lifespan. Therefore, implementing effective speed control mechanisms is essential for maximizing the utility of Brushless DC motors.

In Brushless DC motors, classical controllers are crucial for precise speed regulation and dynamic response. The Proportional, Integral, and Derivative components of the controller continuously adjust the motor's inputs based on the difference between the desired speed and the actual speed. Proportional control adjusts the motor's voltage or current output based on the current error, integral control eliminates steady-state errors by considering past errors over time, and derivative control anticipates future trends in error, enhancing stability. Brushless DC motors often require precise speed control for applications such as robotics, electric vehicles, and industrial automation. PID controllers provide a robust and adaptable solution to meet these requirements, ensuring smooth and efficient motor operation across a wide range of operating conditions.

Fractional order controllers are indeed a captivating area of research in modern control engineering. They are garnering significant attention from researchers due to their potential to outperform traditional integer-order controllers. Fractional control methods, known for their smoother operation and higher efficiency are replacing conventional control techniques that prioritize simplicity and cost considerations. [2] Fractional Order Proportional Integral Derivative (FOPID) controllers are an extension of classical controllers, where the derivative and integral terms are of fractional order. Fractional order controllers offer several advantages over their integer-order counterparts, including better performance in handling non-linear systems, enhanced robustness, and improved disturbance rejection. The motivation for researching a novel approach to designing and validating Fractional Order PID controllers for speed control of Brushless DC motors stems from the increasing demand for precise and efficient motor control in various applications. Traditional PID controllers have limitations in handling nonlinearities and uncertainties present in BLDC motor systems. By exploring Fractional Order PID controllers, this research aims to address these challenges, offering improved control performance, stability, and robustness. The potential benefits include enhanced energy efficiency, reduced wear and tear, and optimized performance in diverse applications such as electric vehicles, robotics, and industrial automation, driving the need for innovative control strategies.

The objectives of the paper are to:

1. Propose a novel approach for designing Fractional Order PID controllers tailored specifically for speed control of Brushless DC motors.
2. Investigate the effectiveness and performance of the proposed controllers compared to traditional PID controllers through simulations.
3. Validate the proposed approach experimentally to assess its applicability and performance.
4. Provide insights into the potential advantages and limitations of employing Fractional Order PID controllers for BLDC motor speed control, offering valuable contributions to the field of control systems and motor control technology.

The section I introduces the FOPID controller and its need for BLDC motor speed control. Section II consists of literature survey in related areas. Section III defines the characteristic equation and mathematical model of BLDC motor; Section IV introduces the importance of fractional order controllers and simulations tools developed by researchers. Section V consists of simulation setups used for modeling fractional order PID based speed control circuits for BLDC motor. Section VI discusses the simulation results for different values and combinations of motor control and performance parameters. Section VII presents the conclusion and discussion of the selection of controller parameters for better performance of motor.

II. STATE OF ART

Researchers have explored various control strategies such as PID control, fuzzy logic control, adaptive control, fractional control and model predictive control to achieve accurate and responsive speed regulation in BLDC motors. In this research authors have referred to many research papers in the relevant area. The research work published around controller selection for BLDC motor control by the authors of this paper has also been cited and referred to.

In a previous work by authors of this paper M. Sharma et al., a different method of controlling Brushless DC motor using PWM-based techniques was explored. PWM techniques, PID controllers, trapezoidal control, and Hall Effect sensors, are essential tools for designers to regulate BLDC motor parameters effectively in electric vehicles. By combining these methods, designers can achieve optimal performance, efficiency, and reliability in BLDC motor control for electric vehicle applications. [1]

In another previous work M. Sharma et al. have also done comparative Analysis of Fractional and Conventional Control Techniques for BLDC Motor Performance Optimization. In this work authors have compared classical and fractional order tuning methods of PID controller for BLDC motor performance parameters. [2] This work discusses the tuning methods for PID controllers in BLDC motor speed control, comparing Ziegler-Nichols, Cohen Coon, and Fractional control techniques. It highlights the parameters obtained from each tuning method and their impact on motor performance.

In a research work by Mohammed et al. [3] a novel control scheme that combines fractional-order PID and fuzzy logic controllers to achieve accurate speed control of a BLDC motor. The proposed hybrid control strategy has been shown to outperform traditional control schemes in terms of speed accuracy and torque ripple reduction. The combination of fractional-order PID and fuzzy logic controllers offers a powerful control strategy that can enhance control performance, adaptability, tuning simplicity, synergistic control, and system stability in complex systems like BLDC motors.

In the work presented by Hafez et al. complex solutions for successful BLDCM speed regulation, such as adaptive sliding and fuzzy mode control approaches are compared. Simulation performance of the established techniques for BLDCM speed regulation is compared to that of a typical Proportional-Integral-Derivative (PID) controller. [4]

Kamranifar et al. [5] have presented a novel approach to controlling their speed using a self-tuning fuzzy PID controller. Simulation results have shown that the self-tuning fuzzy PID controller can provide better performance compared to simple PID controllers. It exhibits reduced overshoot, faster response speed, and improved stability, making it a more effective control solution for BLDC motor speed control.

In a review paper on Fractional Order PID (FOPID)

Based Controllers employed in Brushless DC Motor by Shweta [6] et al., the effectiveness of FOPID controllers in handling uncertain systems is discussed. The study was conducted by researchers to discuss the importance of parameter tuning for improved response and to introduce optimization methods for tuning FOPID controllers.

Jianli Jing et al. [7] discuss fuzzy Proportional Integral and Derivative (PID) controller to improve the performance of conventional fuzzy control in the speed control of brushless DC motors. The proposed fuzzy-PID controller combines the rapid response of fuzzy control with the steady precision of PID control, resulting in excellent dynamic and static performance. The experiment results show that the fuzzy-PID controller outperforms both the conventional PID controller and the conventional fuzzy controller in speed control.

A research paper by Aleksei Tepljakov et al. [8] discusses the use of Fractional-order PID controllers in industrial applications, emphasizing their additional "tuning knobs" for adjusting the control law. It also includes a survey of recent results and applications of these controllers. Recent results and applications of Fractional-order (FO) PID controllers include the use of these controllers in industrial process control, active vibration control of smart composite plates, and synthesis of fractional-order PI controllers and filters for industrial electrical drives.

In the work by Srivastava et al. [9] Particle Swam Optimization based control of BLDC motor is discussed. Performance parameters Kp, Ki and Kv are also calculated and modified based on PSO method.

A research paper by Rameli et al. discusses the self-commutation techniques in BLDC motor. This work also applies the toque control methods using fuzzy PI controller. This technique can be applied to Hybrid Electric Vehicle. [10]

A research paper by Sarojini et al. [11] focuses on speed control of BLDC motor using soft computing techniques. Self-tuned fuzzy controller and conventional controller is compared based on simulations.

The proposed approach by Selmi et al. presents a dedicated algorithm to find faults in BLDC motor Hall Effect sensors. The performance of motor is verified with the help of simulations [12].

Pindoria et al. [13] explore the BLDC motor controller, which is accomplished using Field Programmable Gate Array. The FPGA technologies are used to achieve pulse width modulation-based speed control. These technologies appear to increase dynamic behavior of the BLDC-motor. Simulink and lab models are used to validate these approaches.

In the research paper by Patel et al. [14], adaptive control strategies for brushless DC motors utilizing neural network algorithms to improve speed regulation and response time are presented. Under different load situations and parameter uncertainties, the suggested strategy outperforms conventional approaches in terms of performance.

In the work by Wang et al. [15], three phase BLDC motor control of electric vehicle is presented. The power MOSFETs are used as inverter in the proposed system.

In a review paper by authors of this paper, the fundamentals of the BLDC drive system, converter topologies, as well as the fuzzy logic-controlled BLDC drive system with BLDC motor drives are all examined. This review work presents the comparison of algorithms and methods to control BLDC motor [16].

Time response and frequency response analysis of fractionally control systems is quite important. The transient response of a fractional controlled system includes more parameters to be controlled. The tuning of the fractional control system also provides better control over the parameters. The work contributed by Birs et al. discusses the tuning methods for time-delayed processes [17].

The review article presented by Elmonem et al. [18] explores fractional delayed optimal control, where the control input depends on past states at fractional times, utilizing fractional polynomials for solutions.

Fractional order PID controllers provide self-tuning features to the controller of the BLDC motor. The research work presented by Shamseldin et al. [19] gives a comparison among different tuning methods. Based on these comparisons researchers have tried to find out parameters of sensitive and better tuning of controller.

The study by Zhang et al. [20] proposes a Fractional-Order Controller for Permanent Magnet Synchronous Motors (PMSM) to enhance performance under varying conditions. Simulation and experimental results demonstrate that FOAB-FPID significantly improves acceleration, response time, and disturbance rejection compared to traditional control methods.

Sridhar et al. [21] reported planning, performance and comparative analysis of the speed regulation of a Brushless-DC Motor utilizing a conventional controller like a Proportional Integral (PI) Controller and an ANN-augmented PI controller.

The authors of this paper proposed a superior technique to driving a BLDC-motor by designing an effective motor driver circuit based on the status of the BLDC-motor hall sensors in both running and standalone situations[22].

Brushless-DC motors are gaining popularity in the industrial applications because of their superiority over conventional motors. In this study presented by Saranya et al. [23], the hardware configuration of BLDC motor control system includes a solar-panel, a controller board, an inverter board, MPPT algorithm, a MOSFET driver-circuit, and a communication module.

The study by He et al. [24] introduces an improved Active Disturbance Rejection Control (ADRC) method for brushless DC motors in opto-mechanically scanned systems, featuring mode-switching and harmonic injection to enhance control performance. Experimental results confirm that this method effectively reduces torque ripple and improves system stability.

The work proposed by Deniz et al. presents a time- domain tuning strategy for fractional-order PID controller. To obtain the precise value of error function performance requirement, a Fourier series-based approach (FSM) is utilized to compute the steps responses of the closed loop control systems [25].

Kadwane et al. presented a technique for analyzing the dependability of a BLDC-drive operated by an IGBT based inverter and the entire refrigeration system [26].

The research work done by Matusiak et al. [27] examines the integer and non-integer-based models of the BLDC motor. In such systems, microcontrollers are utilized to make them fractions of non-integer-based systems.

The work presented by Kumari et al. [28] discusses a fractionally built controller for a BLDC motor. To operate a BLDC motor, a conventional PID-controller is substituted with fractional order PID-controller. The BLDC motor dynamic response is tested under various load and speed circumstances.

Khaniki et al. [29] simulated fractional order fuzzy-based controllers which are tuned using the whale optimization algorithm (WOA). Torque ripples in the BLDC motor can be reduced by using these methods to control and tune BLDC motor parameters.

The study by Venu et al. features the Super Twisting algorithm, which uses fractional order sliding mode control to regulate and enhance BLDC motor operations. Simulations are run for various operating modes such as no load, with load, generating, and reverse motoring. Speed and torque responses for BLDC motor with traditional PI-controller and a fractional control-based controller are compared [30].

By conducting the literature survey authors have identified that tuning FOPID parameters can handle the operational challenges of BLDC motor, parameter variations, nonlinearities, etc. Researchers are also actively exploring various aspects of fractional PID controllers. In this paper authors have tried to tune the Fractional order PID controllers for BLDC motor speed control circuit under varying load conditions. It was also observed that suitable optimization method and proper tuning of controller can be helpful for runtime BLDC motor operations.

III. MATHEMATICAL MODELING OF BRUSHLESS DC MOTOR

The BLDC motor is a non-salient-pole-surface permanent magnet machine with a full pitch concentrated winding that produces three-phase trapezoidal counter EMF waves at the machine terminal [3]. The main reason for these motors popularity over their competitors is control simplicity. Fig. 1 shows a Brushless DC motor in self-control mode with an absolute position sensor and voltage-fed inverter.

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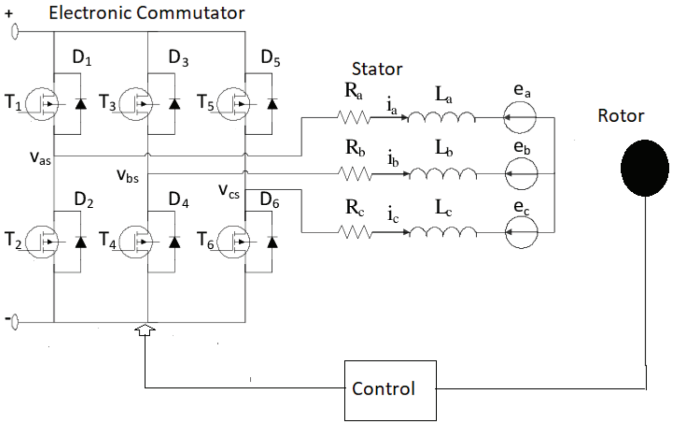


Fig. 1. Self-Controlled brushless DC motor

In terms of motor electrical constants, the coupled circuit equation of the stator winding is expressed as:

$$\begin{matrix}Vas\\Vbs\\Vcs\end{matrix} = \begin{bmatrix}Rs & 0 & 0\\0 & Rs & 0\\0 & 0 & Rs\end{bmatrix}\begin{matrix}ias\\ibs\\ics\end{matrix} + p\begin{bmatrix}Laa & Lab & Lac\\Lba & Lbb & Lbc\\Lca & Lcb & Lcc\end{bmatrix}\begin{matrix}ia\\ib\\ic\end{matrix} + \begin{matrix}eas\\ebs\\ecs\end{matrix} \tag{1}$$

Where:

R_s = Stator Resistance per phase (Assumed equal for all three phases)

e_{as}, e_{bs}, e_{cs} = Induced emf (assumed trapezoidal)

E_p = Peak Value

$E_p = (Blv)N = N(Blr\omega_m) = N\varphi_a\,\omega_m = \lambda_p\,\omega_m$

N= Number of conductors in series per phase

v= velocity

l = length of conductor

r= radius of the rotor bore

ω_m =Angular velocity

B = Flux density of the field in which the conductors are located

The product (Blr) denoted as φ_a , has the dimensions of flux and is directly proportional to the air gap flux φ_g.

$$\varphi_a = Blr = \frac{1}{\pi} B\,\pi lr = \frac{1}{\pi}\varphi_g \tag{2}$$

$\lambda_p = N\varphi_a =$ Flux Linkage

φ_a = Modified Flux Linkage

Because the rotor reluctance does not change with angle due to the non-salient rotor, and assuming three symmetric phases, the following are obtained:

$$L_{aa} = L_{bb} = L_{cc} = L \tag{3}$$

$$L_{ab} = L_{ba} = L_{ac} = L_{bc} = L_{ca} = L_{cb} = M \tag{4}$$

Substituting these values in eq.(1) gives the BLDC model as

$$\begin{matrix}Vas\\Vbs\\Vcs\end{matrix} = Rs\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}\begin{matrix}ias\\ibs\\ics\end{matrix} + p\begin{bmatrix}L & M & M\\M & L & M\\M & M & L\end{bmatrix}\begin{matrix}ia\\ib\\ic\end{matrix} + \begin{matrix}eas\\ebs\\ecs\end{matrix} \tag{5}$$

The stator phase currents are constrained to be balance i.e. $i_{as}+i_{bs}+i_{cs} = 0$

This gives simplified inductance matrix model as:

$$\begin{matrix}Vas\\Vbs\\Vcs\end{matrix} = R_s\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}\begin{matrix}ias\\ibs\\ics\end{matrix} + p\begin{bmatrix}L-M & 0 & 0\\0 & L-M & 0\\0 & 0 & L-M\end{bmatrix}\begin{matrix}ia\\ib\\ic\end{matrix} + \begin{matrix}eas\\ebs\\ecs\end{matrix} \tag{6}$$

The above equations are simplified in terms of transfer function of BLDC motor system by many researchers [4]. By considering the above electrical equations of a three phase BLDC motor, the standard transfer function of BLDC motor is obtained from reference [4] as:

$$G(s) = \frac{1}{s^3} + 3s^2 + 2 \tag{7}$$

This equivalent transfer function obtained from mathematical model of BLDC motor is used to analyze the motor performance metrics like efficiency, speed characteristics and output. Researchers are also working these days for Model validation and verifications of BLDC motor transfer function model. In the literature survey, it was observed that different transfer function models were proposed by researchers for BLDC motor.

IV. FRACTIONAL ORDER PID CONTROLLER

The fractional PID controller was introduced by Podlubny [7]. The controller is called the $PI^{\lambda}D^{\mu}$ controller since it has an integrator of order λ and a differentiator of order μ. The control action of the parallel form $PI^{\lambda}D^{\mu}$ controller can be expressed in the time domain as follows:

$$c(t)=K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \quad (8)$$

Where e(t) is the error signal.

Kp = Proportional gain

Ki = Integral Constant

Kd = Derivative Gain

λ = Order of Integration

μ = Order of differentiation

In the Laplace domain, assuming zero initial conditions, the fractional-order PID controller has the following form:

$$C(s) = K_p + K_i/s^{\lambda} + K_d s^{\mu} \quad (9)$$

Fractional-order control provides additional degrees of freedom as compared to traditional integer-order control, allowing for more flexibility in tuning the controller parameters and potentially improving the dynamic response of the BLDC motor. Conventional PID controllers are based on integer values for the orders of differentiation and integration. In contrast, fractional-order control allows for using non-integer values (fractions) for these parameters. Hence it is also named as $PI^{\lambda}D^{\mu}$ Controller. Here λ is non-integer-order integral and μ is non-integer-order derivative control. [2] Fractionally tuned controller enables improved control of the system, leading to better performance metrics such as lower steady state error, reduced overshoot, and smoother motor operation. Proper selection and thorough tuning of fractional-order controller parameters is necessary to achieve the desired performance gains.

In this research paper, authors used FOMCON toolbox developed by Tepljakov et al. [8] to optimize and tune the fractional order PID controller for BLDC motor control. The FOMCON [8] toolbox for MATLAB is a fractional-order calculus-based toolbox for system modeling and control design. FOMCON consists of a set of useful and convenient tools to facilitate the research of fractional-order systems. This involves writing convenience functions and building Graphical User Interfaces (GUI) to improve the general workflow. A fractional order PID controller has five parameters to tune and control i.e. kp, ki, kd ,λ and μ. FOPID in FOMCON is tuned with the help of Nelder Mead optimization method. The Table (1) displays FOPID tuning and optimization settings in the FOMCON toolbox.

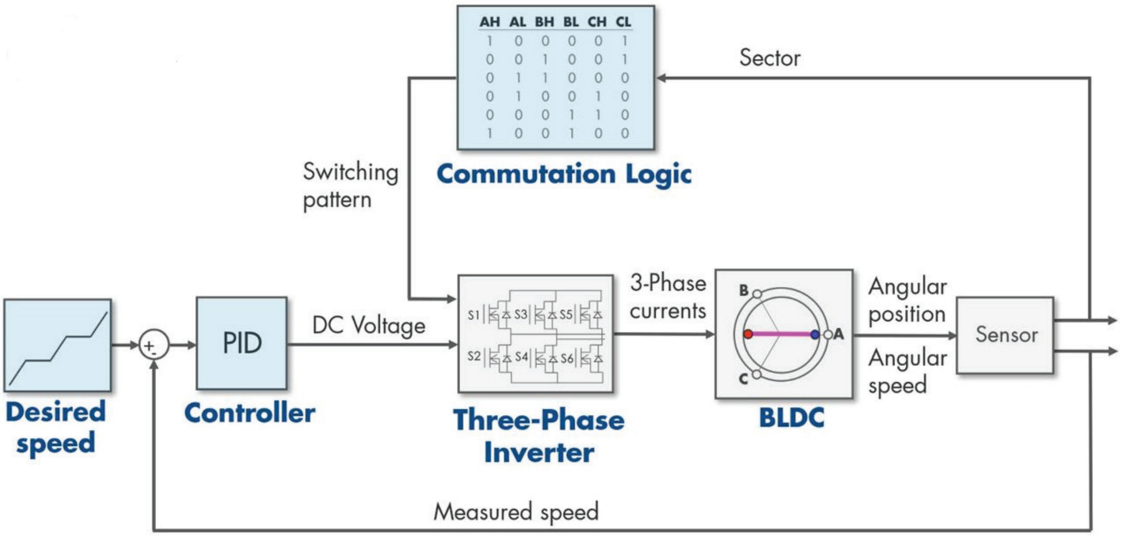
TABLE I
TUNING OF FOPID USING FOMCON.

Process Information		FOPID controlled parameters	
Optimization Algorithm	Nelder Mead Optimization Method	**Kp**	2.5537e-05
Iterations	100	**Ki**	4.8752e-06
Performance Index	8.89523e+24	**Kd**	97.174
Simulation Count	160	**Lambda**	0.010048
Procedure	reflect	**Mu**	0.9

Fractional control parameters kp, ki, kd, λ and μ are tuned and optimized with the help of FOMCON toolbox. Fractional order PID controller is tuned using these values of parameters and this controller is used to control the performance of BLDC motor setup. The performance matrices like maximum overshoot, settling time, rise time are also compared with the conventionally tuned controller of same setup.

V. SIMULATION SETUP

This section presents simulation of conventional speed control circuit of BLDC motor in MATLAB, which is further compared with the fractional order PID based control circuit of BLDC motor. Figure 2 shows the basic setup in MATLAB/Simulink environment for variable speed control circuit of BLDC motor.



AH	AL	BH	BL	CH	CL
1	0	0	0	0	1
0	0	1	0	0	1
0	1	1	0	0	0
0	1	0	0	1	0
0	0	0	1	1	0
1	0	0	1	0	0

Fig. 2. Variable speed control of BLDC motor

A constant/variable DC voltage is provided to the three-phase inverter, resulting in constant speed. By using auto tuned PID controller, this voltage may be changed as per the desired voltage. The controller will change the voltage to bring the motor speed closer to the intended value based on the difference between the desired and measured speeds. The BLDC motor is fed by a controlled three-phase inverter. The gate signals for the inverter are obtained from hall signals.

Figure 3 shows the simulation setup of Ziegler Nichols tuned controller (Classical Control) based speed control circuit of BLDC motor. This is a conventional method to tune the PID controller. In the next section, the response with different combinations of ZN-tuned parameters are shown. In an ealier paper by authors [2] the performance comparison of Conventional PID and Fractional order PID controllers for BLDC motor was done and it was observed that transient response parameters like percentage overshoot and steady state errors are lower when the FOPID controller is used, as compared to the case when conventional PID controllers are used for speed control of BLDC motor.

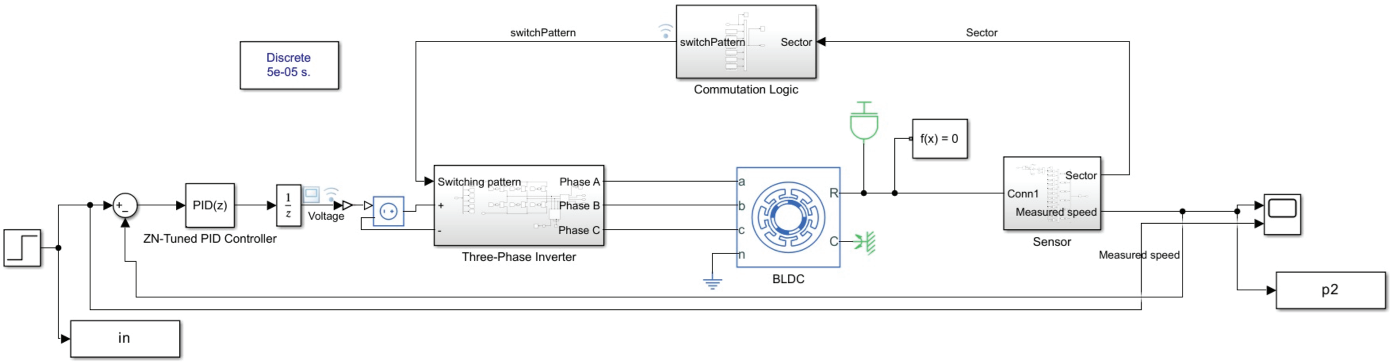


Fig. 3. Simulation setup of ZN-tuned PID controller based BLDC motor speed control circuit

The setup shown in Figure (4) shows the simulation setup of Fractional order PID based BLDC motor speeed control circuit. In this system fractional order PID controller ($PI^{\lambda}D^{\mu}$) block is taken from FOMCON toolbox library. Initially this FOPID is auto tuned with Kp, Ki, Kd,μ and λ. In this work authors have tried to find out the best suitable combinations of all five performance parameters Kp, Ki , Kd, μ and λ to tune the FOPID controller to get improved performance parameters of BLDC motor.

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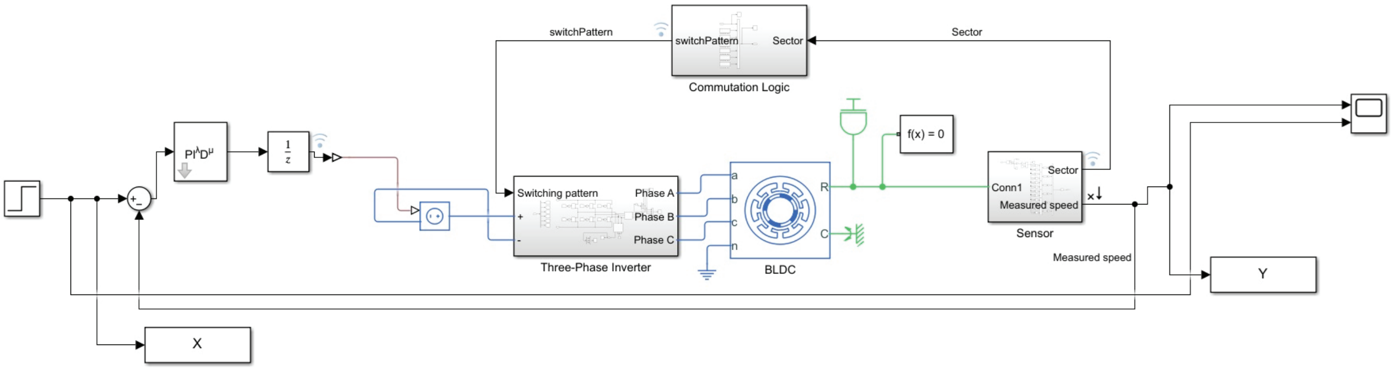

Fig. 4. Simulation of FOPID based BLDC motor speed control circuit

The next section shows the simulation results of Figures 3 and 4 for different combinations of performance parameters of controller. The novel approach proposed in this paper validates the FOPID controller parameters for improved performance parameters with the help of simulation results.

VI. RESULTS AND DISCUSSION

This section shows the result of speed control of BLDC motor using conventional PID controller and fractional order PID controller. Conventional tuning method is used to tune the PID controller. Different values of Proportional gain Kp, Integral gain Ki and Derivative gain Kd are tried for simulation as shown in Table I. Step response of BLDC motor for different values of Kp, Ki and Kd are shown in Figure 5.

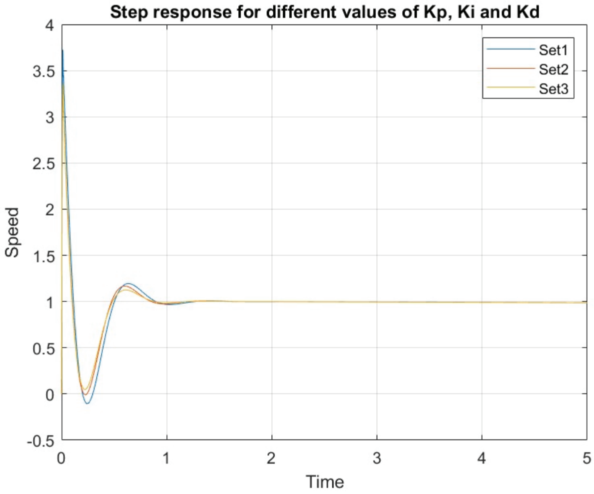

Fig.5. Speed response for different sets of Kp, Ki and Kd for conventional controller

To evaluate the performance of step response, different sets of performance parameters are taken into consideration. The parameters are peak overshoot, peak time rise time and settling time. For different values of proportional gain, derivative gain and integral gain the values of the parameters are shown in Table II.

TABLE II
PERFORMANCE PARAMETERS FOR DIFFERENT VALUES OF Kp, Ki AND Kd.

	Kp	Ki	Kd	Rise Time (sec)	Settling Time (sec)	Overshoot	Peak Time (sec)
Set 1	0.05	1.23	0.032	1.1	8.57	157.76	0.011
Set 2	0.03	1.12	0.012	0.92	3.84	73.631	0.013
Set 3	0.02	1.05	0.01	0.913	3.6	54.1	0.014

Figure 5 shows the speed response of conventional control-based system. It has greater overshoot and settling time. This conventional system is also simulated with varying load conditions. The effect of load variation is clearly seen in Figure 6. There is large difference in overshoot of the system with changes in load of the motor.

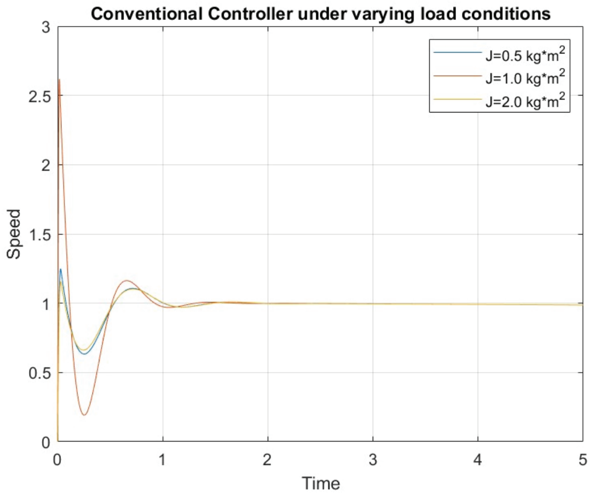

Fig. 6. Effect of load variation on Conventional Controller

Further, the same BLDC motor system is simulated by replacing the controller as fractional order controller and the system response is observed for different combinations of λ and μ.

Fractional order control has more degree of freedom. It provides control over the five parameters of PID controller i.e, Kp, Ki, Kd, λ and μ. In fractional controllers, the order of the integral and derivative gain are in fractions. This paper evaluates the performance of the controller with different combinations of λ and μ and tries to find the best combination of λ and μ in a heuristic method.

Different combinations of λ and μ are shown below:

i. λ = 1 and 0.1 < μ < 1

ii. 0.1 < λ < 1 and μ = 1

iii. 0.1 < λ < 1 and 0.1 < μ < 1

iv. λ = > 1 and μ > = 1

i. *With λ =1 and varying values of μ<1*

Figure 7 shows the speed response of BLDC motor with λ =1 and varying values of μ<1. It is observed that by reducing the values of μ, the response become smoother with reduced overshoot and lesser settling time.

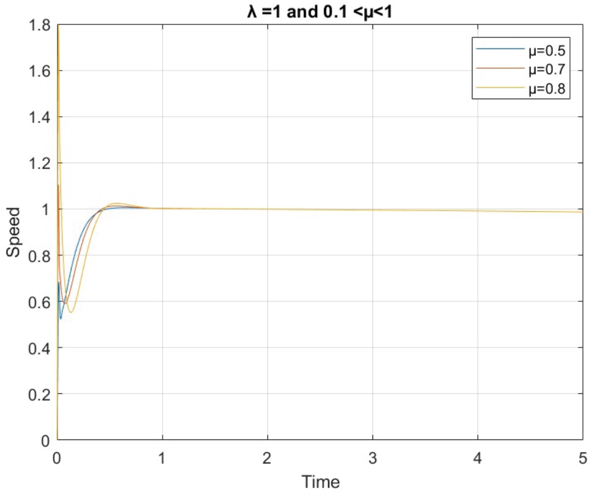

Fig. 7. Step response of BLDC motor control using FOPID for λ =1 and different value of μ<1

The transient and steady state parameters of step response with different combinations of λ and μ are shown in table III. Overshoot is minimum for lesser values of μ. The system also settled fast for lesser values of μ.

TABLE III
COMPARISON OF PARAMETERS FOR DIFFERENT COMBINATION OF λ AND μ.

λ	μ	Rise Time (sec)	Settling Time (sec)	Overshoot	Peak Time (sec)
1	0.5	9.84 ms	1.01	6.2	0.642
1	0.7	5.88 ms	1.005	10	0.012
1	0.8	99.8 ms	3.6	54	0.014
1	0.9	5.523	3.6	40	0.013

ii. *With λ <1 and μ=1*

Figure 8 shows the step response of speed control of BLDC motor with μ=1 and varying values of λ <1. It can be observed that μ values less than 0.7 give better response. If μ is moving towards more than 1, response becomes oscillatory and unstable.

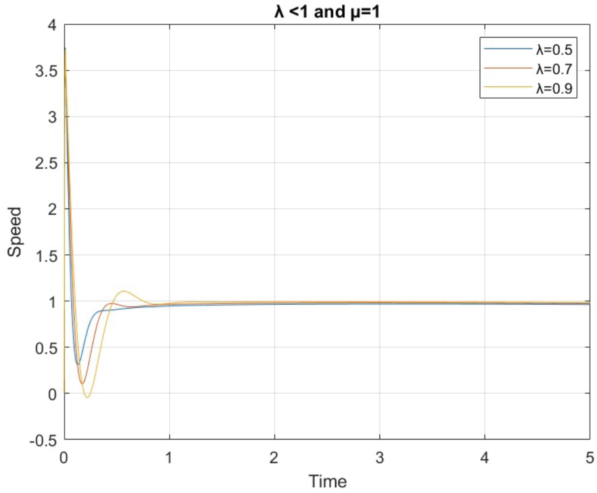

Fig. 8. Step response of BLDC motor control using FPID for μ=1 and different value of λ <1

TABLE IV
COMPARISON OF PARAMETERS FOR DIFFERENT COMBINATION OF λ AND μ.

λ	μ	Rise Time (sec)	Settling Time (sec)	Overshoot	Peak Time (sec)
0.5	1	5.57 ms	3.74	314.53	0.012
0.7	1	4.42 ms	3.72	303	0.012
0.8	1	4.43 ms	3.72	300	0.012
0.9	1	4.43 ms	3.72	296	0.012

The transient and steady state parameters of step response with different combinations of λ and μ= constant are shown in table IV. It can be observed that overshoot is minimum for lesser values of λ, this also reflects that μ=>1 gives no acceptable values of overshoot even if settling time is reduced.

iii. With λ <1 and μ<1

Figure (9 a , b ,c) shows the step response of speed control of BLDC motor with varying values of λ and μ. This observation is taken for three different setups i.e. μ =0.5 μ=0.7 and μ=0.9 with varying values of λ <1 for each set. This can be observed that λ <0.5 and μ<0.5 shows good transient response, there is less overshoot, settling time has also reduced a lot. System gets settled down very quickly. Overshoot is also acceptable as comparison with other combination of λ and μ.

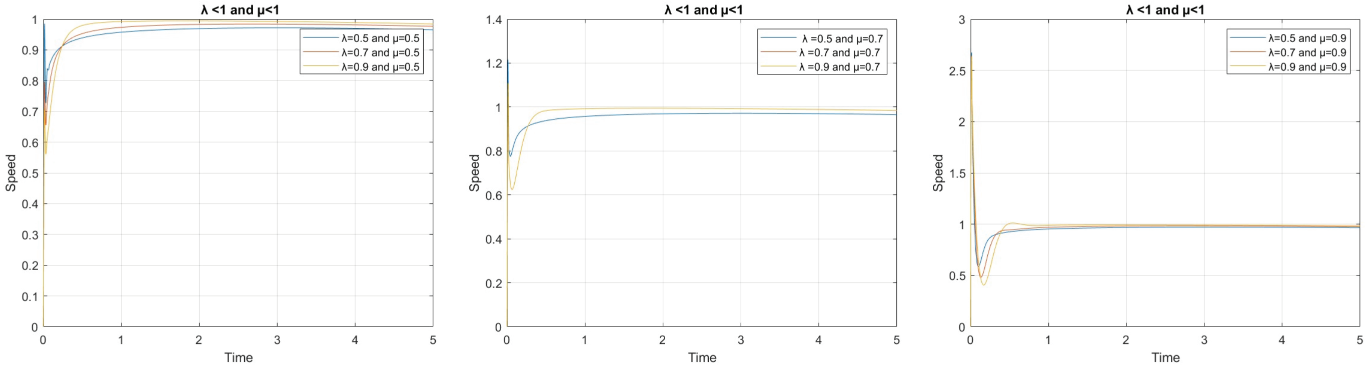

Fig. (9 a, b, c). Step response of BLDC motor control using FPID for different value of λ <1 and μ<1(0.5, 0.7 and 0.9)

The transient and steady state parameters of step response with different combinations of λ and μ with varying values are shown in table V. Overshoot is minimum for lesser values of λ and μ. It can be stated that λ <1 and μ<0.7 can be opted for better performance depending upon the application.

TABLE V
COMPARISON OF PARAMETERS FOR DIFFERENT COMBINATION OF λ AND μ.

λ	μ	Rise Time (sec)	Settling Time (sec)	Overshoot	Peak Time (sec)
0.5	0.5	9.1 ms	0.98	9.01	0.017
0.7	0.5	5.4 ms	0.98	6.480	2.66
0.9	0.5	8.4 ms	0.99	5.800	1.806
0.5	0.7	4.88 ms	1.20	34.000	0.013
0.7	0.7	4.8 ms	1.10	26.000	0.012
0.9	0.7	5.73 ms	1.10	18.030	0.012
0.5	0.9	5.58 ms	2.67	196.000	0.013
0.7	0.9	5.5 ms	2.64	186.300	0.013
0.9	0.9	5.23 ms	2.63	180.530	0.013

iv. With λ >=1 and μ>=1

It is observed that values of λ and μ greater than 1 show poor response and that system overshoot becomes very high. System takes much time to settle down.

The transient and steady state parameters of step response with λ >=1 and μ >=1 varying values are shown in table VI. With λ=1 and μ=1 fractional PID behaving like conventional PID and response for the BLDC motor control is not acceptable. The transient response becomes oscillatory and sluggish. System Moves towards instability.

TABLE VI
COMPARISON OF PARAMETERS FOR DIFFERENT COMBINATION OF λ AND μ.

λ	μ	Rise Time	Settling Time	Overshoot	Peak Time
1	1.2	36 ms	4.19	830.22	0.062
1.1	1	71 ms	3.9	2.91	0.012
1.3	1	72 ms	3.5	2.87	0.012
1.5	1	72 ms	2.99	283.88	0.012
1.7	1	72 ms	4.77	284.06	0.012

This Fractional order controller-based system of BLDC motor was also simulated under varying load conditions. Figure 10 shows that the performance parameters and the response of the motor control system remains the same for different load conditions. If it is compared with the varying load response of the conventional controller based system as shown in Figure 6 , it clearly shows that FOPID based system tries to maintain the desired system response whereas there is a big change in the system response of conventionally tuned system in terms of overshoot, settling time and other performance parameters.

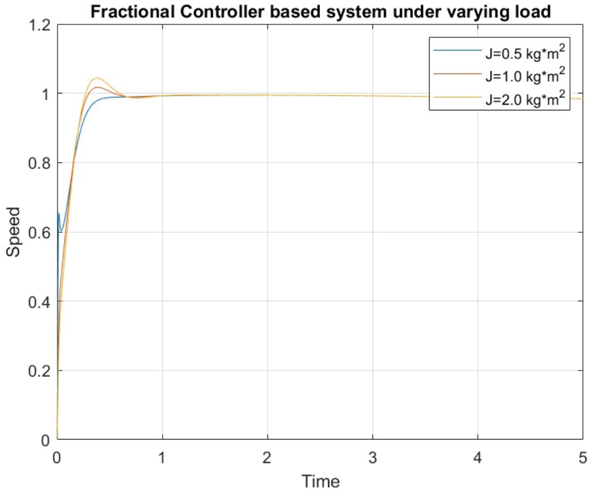

Fig. 10. FOPID based system under varying load

Table VII shows the comparison of performance parameters of PID and FOPID controllers under varying load conditions. This can be clearly observed from the table that performance parameters of FOPID controller-based system have very less overshoot, rise time, settling time and peak time as compared to conventional PID controller-based system. As the load increases, PID controller-based system does not give a stable response, whereas with increasing load also FOPID based system offers a stable and improved performance.

TABLE VII
COMPARISON OF PARAMETERS WITH VARYING LOAD.

	J1=0.5kg*m^2		J2=1kg*m^2		J=2kg*m^2	
	PID	FOPID	PID	FOPID	PID	FOPID
Rise Time (Sec)	0.8	0.218	0.11	0.214	0.75	0.151
Settling Time (Sec)	2.5	0.408	3.8	0.315	2.9	0.604
Overshoot (Sec)	19%	0.605%	30%	1%	89%	9.3%
Peak Time (Sec)	0.19	0.400	0.1	0.305	0.023	0.389

This rigorous simulation-based verification of the proposed FOPID controller performance ensures that the proposed FOPID controller meets the desired performance objectives. It also shows the impact of changes in controller parameters on system performance. Iterative refinement in FOPID controller parameters based on simulation results optimizes the system performance. This comprehensive simulation study rigorously validates the performance of the proposed FOPID controller and gains confidence in its ability to meet the desired control objectives for the BLDC motor application.

VII. CONCLUSION

This paper analyses the use of fractional order proportional integral derivative (FOPID) controller for speed control of brushless direct current (BLDC) motor. Simulations have shown the variations in step response of the system if the derivative and integer order of the fractional controller is varied. This approach can be used to obtain the optimal values of integer order and derivative order control parameters to control the speed of BLDC motor for various applications in industries.

It has been also observed that $\lambda < 1$ and $\mu < 0.7$ have shown the better response and performance parameters as comparison with other combinations of λ and μ. Different sets of λ and μ have been tried for finding better response of BLDC motor speed control circuit. It has been proved with the help of simulation results that fractional order controller for BLDC motor operations can be preferred over conventional controller. Fractional controller-based system gives optimal system performance, robustness, and adaptability to complex dynamics.

In comparison with conventionally tuned controller, fractionally tuned controller-based control circuit of BLDC motor has shown a significant impact on transient response of the system. The findings clearly show the impact of better transient response on fast response time and reduced overshoot. Reduced rise time, overshoot and settling time significantly influence the transient response of the system. Hence it can be concluded that fractionally tuned controller provides the optimal system performance with desired design specifications. fractional order proportional integral derivative (FOPID) controller can be a better choice for different industrial applications where system performance, efficiency, and stability are important factors like chemical plants, oil refineries wind turbines automotive industry, aerospace industry, marine Industries and many more.

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