RESEARCH ARTICLE

Asian Research Association

INTERNATIONAL RESEARCH JOURNAL OF MULTIDISCIPLINARY TECHNOVATION

DOI: 10.54392/irjmt25511

Hybrid GWO-PSO Based Optimal PID Controller for Brushless PMDC Motor

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DOI: https://doi.org/10.54392/irjmt25511

Received: 21-02-2025; Revised: 29-08-2025; Accepted: 17-09-2025; Published: 28-09-2025

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Abstract: This article presents an optimized design and tuning approach for Proportional-Integral-Derivative (PID) controllers applied to brushless Permanent Magnet Direct Current (PMDC) motors, widely used in industrial automation, robotics, and electric vehicles for their efficiency and precision. Traditional tuning methods like the Ziegler-Nichols (ZN) often fall short in handling the nonlinear and dynamic behavior of PMDC motors. To overcome these limitations, nature-inspired algorithms (NIAs) including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and a proposed hybrid GWO-PSO approach are utilized to enhance controller performance. The hybrid GWO-PSO algorithm combines the exploration strength of GWO with the exploitation capabilities of PSO, yielding superior optimization outcomes. A detailed PMDC motor model is developed in MATLAB/Simulink to assess each controller based on transient response, set-point tracking, disturbance rejection, and robustness. Simulation results indicate that the hybrid GWO-PSO-PID controller reduces rise time, overshoot, and settling time compared to the standard GA-PID, PSO-PID, and GWO-PID controller. It also shows better disturbance rejection and stability margins. These findings highlight the hybrid approach's effectiveness in improving control performance, offering a reliable solution for real-time PMDC motor applications.

Keywords: Brushless PMDC motor, Genetic Algorithm (GA), Grey Wolf Optimization (GWO), Hybrid GWO-PSO algorithm, Nature-Inspired Algorithms (NIA), Particle Swarm Optimization (PSO), PID controller, Ziegler-Nichols (ZN) Method.

1. Introduction

The development of advanced control systems for brushless PMDC motors has significant attention due to their widespread application in industrial automation, robotics, and electric vehicles. Achieving efficient and optimal motor control remains challenging, particularly in the presence of nonlinearities or external disturbances. The applications of this motor are used in drones and quadcopters for rotor propulsion, camera gimbal stabilization, folding mechanisms, and payload control. They are lightweight, compact, cost-effective, and offer simple speed control with high torque at low speeds, making them ideal for small, battery-powered aerial systems. Deepak *et. al.* [1] presents papers on review of various BLDC motors and their challenges in controls applications. Chen [2] presents the PID controller's flexibility and usefulness make it one of the most used control systems. However, traditional tuning methods like ZN often fail to deliver optimal performance, especially for complex systems like PMDC motors, due to their dependency on trial and error and limited ability to handle nonlinearity and uncertainties. Fajuke and Raji present PID controller application in speed control of DC motor [3].

The development of NIAs has influenced controller tuning in recent years. Ramakant Patil *et. al.* [4] gives a review on various NIAs methods are used for PID tuning with comparison. Techniques like GA, PSO, and GWO have tremendous potential to address the drawbacks of traditional tuning methods. Borase *et. al.* [5] gives review on PID control and tuning methods with applications. Due to their strong search capabilities and inspiration from natural occurrences, NIAs algorithms are used to solve non-linear and multi design optimal problem. Genetics and natural selection inspire the optimization method known as GA. For example, Meena and Devanshu [6] presents the application of GA in process control using PID and Ibrahim *et. al*. [7] presents brushless DC motor PID control using GA. GA may require many generations to converge to optimal PID parameters, making it computationally intensive and less suitable for real-time or time-critical applications. PSO modeled on the social behavior of bird flocks, excels in rapid convergence but often struggles to avoid local optima. For example, Munje and Medewar [8] presents the application of PSO for PMDC motor control using PID and Xu [9] presents speed control of electric vehicles using PSO-PID. PSO limits its ability to adapt the PID parameters dynamically during real-time operation of the PMDC motor control. GWO, on the other hand, shows great global search capabilities but may have slower convergence rates because it is modelled after the hierarchical hunting strategy of grey wolves. Hocaoglu *et. al.* [10] presents paper on load frequency control using GWO-PID and Pawlowski *et. al*. [11] presents PMDC motor parameter estimation using GWO. The performance of GWO in load frequency control and motor parameter estimation heavily depends on proper tuning of its control parameters and suboptimal settings can lead to premature convergence or inaccurate results. This paper suggests a hybrid GWO-PSO algorithm that combines the exploring advantages of the GWO with the utilization potential of PSO in order to address these problems. The goal of this hybrid approach is to provide a more balanced and successful optimization technique by overcoming the separate shortcomings of PSO and GWO.

The various literature in publications has examined the designing of PID controller using nature inspired or metaheuristics or modern computational algorithms for different applications like the combination of simulated annealing and white shark optimization aims to enhance the tuning of PID controllers for automatic voltage regulation [12], PID controller adjusted by ant colony optimization (ACO) and symbiotic organism search (SOS) can be used to regulate the temperature and relative humidity of the cozy space. [13], control of PID controller in industrial applications [14], PID tuning using metaheuristic algorithms [15], the traditional PID tuning with metaheuristic algorithms of complex systems [16], PID tuning using modern computational algorithms [17], and various NIAs for continuous function optimization [18]. Additionally, the design of a wireless PMDC motor using wireless power transfer (WPT) technique [19], the use of an FPGA controller for PMDC motor speed control [20], PMDC motor speed control by closed-loop [21], the calculation of motor parameters and its speed for a wheelchair application [22], the design of a fractional PID controller for PMDC motor speed control [23], the development of NIA using oceans to space nature activity and the review of heuristic optimization algorithms and their applications in drones [24], and the design of I-D controller for a boost converter using NIA's [25].

However, there is limited research on hybrid algorithms that synergize multiple optimization techniques for PMDC motor control. The intends to bridge this gap and add to the expanding corpus of research on sophisticated motor control techniques by presenting the hybrid GWO-PSO algorithm. By combining the complimentary advantages of PSO and GWO into a single framework for PID tuning, this study makes a significant contribution. The hybrid GWO-PSO effectively balances global search (to avoid local optima) with faster convergence (to refine optimal solutions). Unlike other hybrids that lean heavily on either exploration (e.g., GA-GWO) or exploitation (e.g., PSO-ABC), this method dynamically fuses both behaviors using shared population updates and combined position formulas.

The suggested method performance is compared to standalone GA, PSO, GWO, and conventional ZN approaches through simulation using MATLAB software. The results demonstrate the hybrid algorithm's effectiveness, resulting in improved motor control, quicker convergence, and greater adaptability. Using the proposed hybrid technique, the PID controller parameters of a brushless PMDC motor are tuned to improve system performance metrics like robustness, maximum overshoot, fast settling time, and negligible steady state error. The paper is outline as, Section 2 explains modelling of brushless PMDC motor. Section 3 discuss the PID controller and control strategies of brushless PMDC motor. The design of PID controllers using tuning methods such as ZN, GA, PSO, and GWO are discuss in Section 4. The designing and implementation of proposed hybrid GWO-PSO-PID controller present in Section 5. In Section 6, analysis of obtained results in terms of step response, set point tracking, disturbance, robustness of proposed controller and speed control of motor through MATLAB simulation circuit and characteristics of motor are discuss. Finally, Section 7 concludes this paper with future scope.

2. Brushless PMDC Motor Model

Brushless PMDC motors and conventional DC motors are similar, with the primary difference being the addition of phases in brushless PMDC motors, which eliminates the need for brushes and it impacts their overall performance, enabling smoother torque production, greater efficiency, reduced maintenance, and better dynamic response [26, 27]. This makes brushless PMDC motors particularly well-suited for precision applications in robotics, electric vehicles, and automation systems. Figure 1 is the equivalent circuit diagram shows the whole-phase concept of the brushless PMDC motor with a symmetrical 3-phase and star internal connection. The mathematical model is derived from a conventional DC motor. The transfer function given by equation (1), represents a second-order linear system derived from the electromechanical dynamics of a brushless PMDC motor. This model captures both electrical and mechanical dynamics through the electrical time constant T_e and mechanical time constant T_m, whose precise estimation is critical for accurate control and system identification.

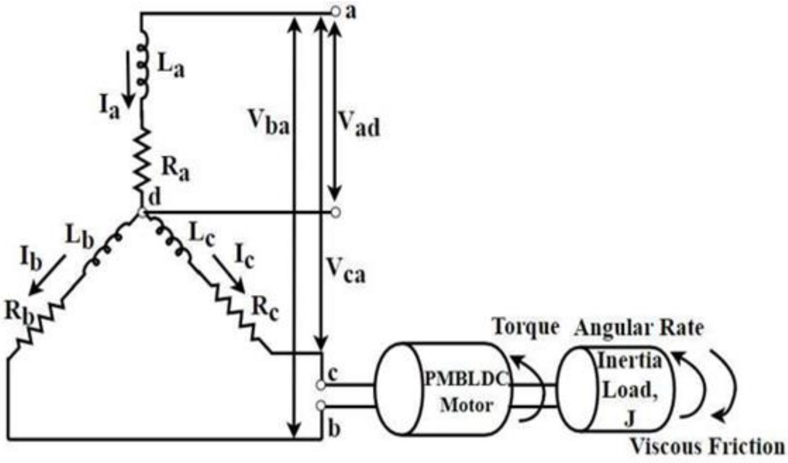

Figure 1. Equivalent Circuit of Brushless PMDC Motor

$$G(s) = \frac{1/K_e}{T_mT_es^2+T_ms+1} \tag{1}$$

Taking into account their phase effects, the brushless PMDC motor has a significant impact on the mechanical time constant shown in equation (2),

$$T_m = \sum \frac{RJ}{K_eK_t} = \frac{J\sum R}{K_eK_t} \tag{2}$$

where, R is resistance of winding, J is moment of inertia of the rotor, K_t is the torque constant. When operating in a three-phase symmetrical configuration, the mechanical constant equation (3) obtained and it highlighting that the number of motor phases directly impacts mechanical dynamics and increase effective resistance, resulting in a longer mechanical time constant.

$$T_m = \frac{3RJ}{K_eK_t}. \tag{3}$$

Similarly, the electrical time constant in equation (4), accounts for the distributed resistance across the motor's three phases.

$$T_e = \sum \frac{L}{R} = \frac{L}{\sum R} = \frac{L}{3R} \tag{4}$$

where, L is the inductance of winding. R and L affect the speed of current response. J and B (viscous friction coefficient) determine the motor rotational inertia and damping. The mechanical and electrical subsystems are connected via K_e and K_t. After substituting values of electrical parameters of motor from Table 1 in above equations, obtained $T_m = 0.00136, T_e = 0.00232$ and the motor model as shown in equation (5). This model of brushless PMDC motor is used for PID controller design using ZN, GA, PSO, GWO, and hybrid GWO-PSO algorithms. In drone application, to fly smoothly, consume power efficiently, and react quickly to changes in the environment and human commands, its motor speed and position must be precisely, steadily, and adaptively controlled.

$$G(s) = \frac{23.04}{0.00315s^2+0.00136s+1} \tag{5}$$

Table 1. Parameters of Brushless PMDC Motor

Electrical parameters	**Values**
Motor Inertia	0.00189 Kgm^2
Voltage Constant	0.0434 Vs / rad
Torque Constant	0.0434 Nm/A
Resistance	0.045 Ω
Inductance	0.314 mH

The brushless PMDC motor open-loop step response is shown in Figure 2(a). It is an underdamped response with a decaying envelope, in which oscillations are first seen in the system and eventually decrease until a steady-state value is reached. Time domain parameters such as peak overshoot of 96.3% and settling time of 18s were derived from the motor open loop dynamics. It provides a clear and simple picture of the motor behavior, the lack of feedback control in an open-loop system makes it unsuitable for applications requiring precision, stability, and disturbance rejection. The bode plot of the motor model provided by equation (5) is displayed in Figure 2(b). Using the Bode stability criterion, the system frequency response is evaluated. The system is stable because gain margin (∞dB), phase margin (0.30^0), gain crossover frequency (∞dB), and phase crossover frequency (87.36dB) of the system.

3. Control Strategies

Due to the reliability and simplicity, PID controller is generally used in process industries. The structure of PID controller is shown in Figure 3 [28]. K_P determines the response to current error, K_I eliminates steady-state error by considering the cumulative error and K_D predicts error trends and adds damping to reduce overshoot. Apply classical ZN or NIA such as GA, PSO, GWO and hybrid GWO-PSO for PID tuning.

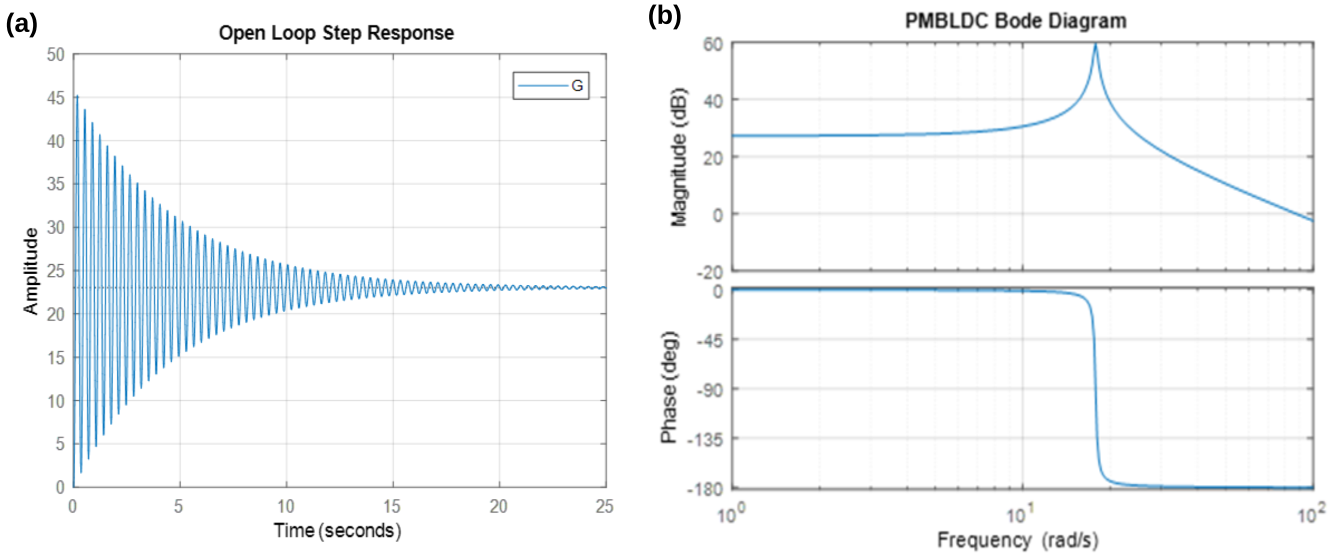

Figure 2. Open-loop (a) step response and (b) frequency response of PMDC motor

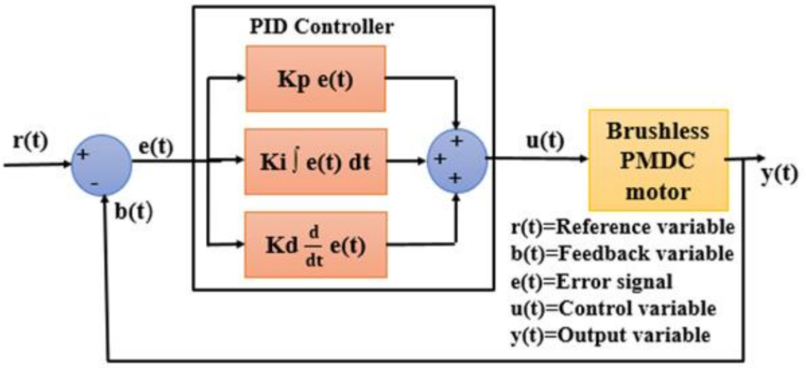

Figure 3. Block Diagram of PID Controller

The PID controller generates the output is known as control signal u(t) shown in equation (6) and it apply to the motor input voltage to adjust its speed or position. The model (transfer function) of the PID controller equation (7), derived by applying Laplace transform to equation (6). Simulate the motor model and controller using MATLAB/Simulink.

$$u(t) = K_P\, e(t) + K_I \,(\int_0^t e(t)dt) + K_D\, (\frac{de(t)}{dt} \qquad (6)$$

$$Y(s) = K_P + (\frac{K_I}{s}) + K_D s \qquad (7)$$

The control strategy or scheme of brushless PMDC motor is shown in Figure 4, where a PID controller processes the error between the reference and actual speeds [29]. PID parameters are optimized using advanced algorithms like GA, PSO, GWO, and hybrid GWO-PSO to achieve efficient performance. In order to determine how well the optimization algorithms and PID controller minimize errors, Integral Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE), Integral Squared Error (ISE), and Integral of Time-weighted Squared Error (ITSE) measures the total error over time using equations (8) to (11). The output of PID controller is connected to PWM block and produce the output that controls the universal bridge switching to regulate motor voltage. Gates, Logical Operator, and Decoder elements process the PWM signals and manage the commutation process in synchronization with the motor rotor position, which is detected via the Hall Effect sensors.

Universal Bridge serves as the power electronic interface for converting the DC source into the appropriate form required to drive the brushless PMDC motor. The motor converts the electrical input into mechanical motion (rotor speed). It is the primary component being controlled in the system. The system monitors key parameters, such as stator currents and electromagnetic torque.

$$\mathrm{IAE} = \int_0^\infty |e(t)|dt \qquad (8)$$

$$\mathrm{ITAE} = \int_0^\infty t|e(t)|dt \qquad (9)$$

$$\mathrm{ISE} = \int_0^\infty e^2\,(t)dt \qquad (10)$$

$$\mathrm{ITSE} = \int_0^\infty te^2\,(t)dt \qquad (11)$$

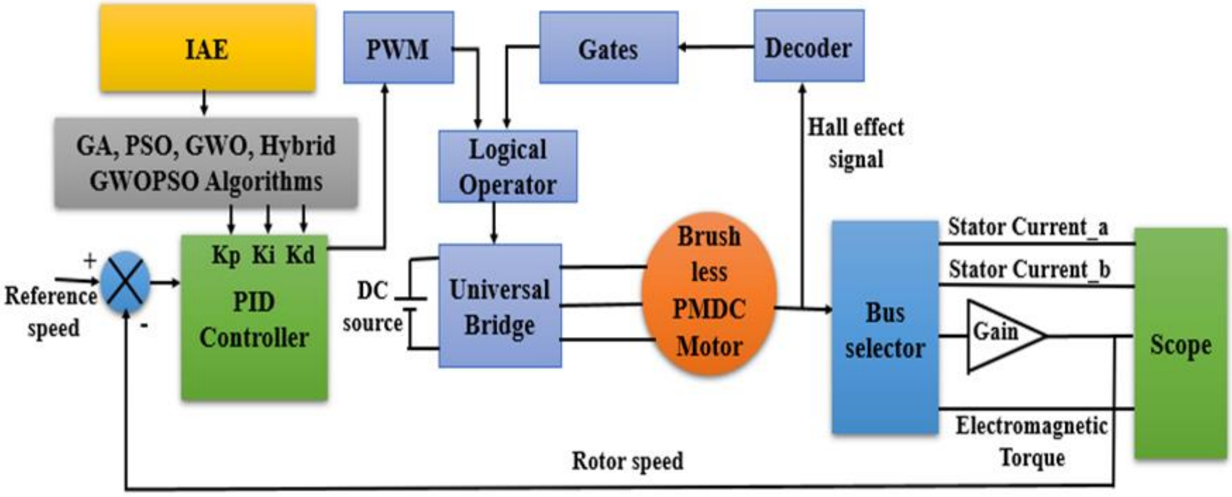

Figure 4. Block Diagram of Brushless PMDC Motor Control Strategy

4. PID Controllers Design

4.1 ZN-PID Controller

Use the ZN closed-loop (critical gain and period) tuning approach [30] for finding the PID setting and then by using these values design ZN-PID controller as indicated in equation (12). The ZN tuning method is easy to implement and provide a good starting point, but limitations make it less suitable for nonlinear, or time-varying systems like brushless PMDC motors. It is tedious and do not yield the best possible gain values. Thus, advanced techniques like NIA are more effective for achieving optimal and robust performance.

$$\text{ZN-PID} = 0.66 + \left(\frac{20}{s}\right) + 0.0054s \qquad (12)$$

4.2 GA-PID Controller

It is an optimization technique that simulates natural selection to find optimal solutions [31]. A population consists of potential solutions (chromosomes), each encoded with values (genes) representing variables like K_P, K_I, and K_D in PID tuning. The fitness function evaluates the quality of each chromosome, using metrics like IAE. Operators guide evolution: selection picks the best-performing solutions for reproduction, crossover combines parents to create offspring, and mutation introduces random variations to maintain diversity and avoid local optima. This iterative process continues until an optimal solution is found. By using this optimal solution with population size (10), iterations (5), mutation rate (0.1) and IAE objective function, design GA-PID controller for brushless PMDC motor as shown in equation (13). GA is highly complex, offers slower convergence depending on population and generations, is robust to local optima, highly adaptable with wide applicability, and provides gradual performance improvement based on mutation and crossover rates.

$$\text{GA-PID} = 0.9765 + \left(\frac{6.0604}{s}\right) + 0.0968s \qquad (13)$$

4.3 PSO-PID Controller

PSO is based on social behavior of fish populations and bird flocks [32, 33]. It uses particles that travel in the search space and discover the required solution. Every particle has a location that signifies a possible solution and a velocity that dictates how far it travels. Particle performance is evaluated using a fitness function. Both gBest (global best position) and pBest (particle's personal best position) are tracked. Each iteration updates the position and velocity according to exploration (distance from pBest) and exploitation (distance from gBest). PSO development steps:

Step 1: In the search space, generate a population of particles with random positions and speeds. Next, assign a random initial pBest position to every particle. Lastly, use each particle's fitness to find its gBest position.

Step 2: Use the objective function to assess each particle fitness.

Step 3: Use equation (14) for updating the velocity of each particle.

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 \left(pBest_i - x_i^k\right) + c_2 r_2 \left(gBest - x_i^k\right) \qquad (14)$$

Where the best position of an individual particle is represented by pBest, the best position of the group by gBest, the inertia weight by ω=0.7, the acceleration constants c_1=c_2=1.5, the random values r_1, and r_2 in the interval [0, 1], and the current position and velocity of particle 'i' at iteration 'k' are represented by x_i^k and v_i^k, respectively.

Step 4: According to equation (15), update each particle position using its new velocity.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \qquad (15)$$

Step 5: Update each particle pBest if the current position improves the fitness and update the gBest if any particle fitness is better than the current global best.

Step 6: For a predetermined number of iterations, repeat steps 2 through 5.

Step 7: Return the gBest as the optimal solution.

After getting optimal solution using population size (10), iterations (5), and IAE objective function, design PSO-PID controller for brushless PMDC motor as shown in equation (16). PSO has moderate complexity, initially fast convergence with a risk of premature convergence, moderate robustness and adaptability dependent on parameters, and rapid initial performance improvement that may plateau.

$$\text{PSO-PID} = 1.7658 + \left(\frac{7.2401}{s}\right) + 0.1150s \qquad (16)$$

4.4 GWO-PID Controller

GWO is optimization method inspired by nature [34, 35]. Alpha (α) represents the best solution, Beta (β) signifies the second-best solution, Delta (δ) corresponds to the third-best solution, and Omega (ω) refers to the rest of the wolves. This hierarchy emulates the social structure and hunting strategies of grey wolves. In order to imitate optimization, the wolves cooperate to encircle and seize prey. GWO employs adaptive parameters to balance exploration, which involves discovering new solution spaces, and exploitation, which focuses on refining existing solutions, making it effective for both continuous and discrete optimization problems. GWO development steps:

Step 1: Decide how many grey wolves to use, choose a maximum number of iterations, and start the population of wolves (solutions) at random points in the search space. Use the objective function to assess each wolf's fitness. Determine which wolves are the best in terms of fitness and mark them as α (best), β (second-best), and δ (third-best).

Step 2: Calculate the control parameters $\vec{a}$ and $\vec{A}$, where $\vec{a}$ decrease from 2 to 0 on iterations and $\vec{A} = 2\,\vec{a}\,\vec{r_1} - \vec{a}$. Compute $\vec{C} = 2\,\vec{r}$, where $\vec{r}$ = [0, 1].

Step 3: Compute the distances as per equations (17-19) between the positions of a wolf and α, β, δ wolves:

$$\vec{D_\alpha} = |\vec{C_1}\,\vec{X_\alpha} - \vec{X}\,|, \text{ and } \vec{X_1} = |\,\vec{X_\alpha} - \vec{A_1}\vec{D_\alpha}\,|, \qquad (17)$$

$$\vec{D_\beta} = |\vec{C_2}\,\vec{X_\beta} - \vec{X}\,|, \text{ and } \vec{X_2} = |\,\vec{X_\beta} - \vec{A_2}\,\vec{D_\beta}|, \qquad (18)$$

$$\vec{D_\delta} = |\vec{C_3}\,\vec{X_\delta} - \vec{X}\,|, \text{ and } \vec{X_3} = |\,\vec{X_\delta} - \vec{A_3}\vec{D_\delta}|. \qquad (19)$$

And update position using equation (20) of the wolf ($\vec{X}$) with effect of α, β, δ:

$$\vec{X}(k+1) = \left(\frac{\vec{X_1}+\vec{X_2}+\vec{X_3}}{3}\right) \qquad (20)$$

Step 4: After the wolves' placements have been updated, assess each one's fitness. Adjust α, β, and δ in accordance with the updated fitness values.

Step 5: Repeat steps 2 to 4, until the final iteration is achieved.

Step 6: Return at α position and which is optimal solution.

After getting optimal solution using population size (10), iterations (5), and IAE objective function, design GWO-PID controller for brushless PMDC motor as shown in (21). GWO has low complexity, slower initial convergence with balanced progress later, high robustness with minimal parameter sensitivity, high adaptability requiring minimal tuning, and consistent performance with effective global search.

$$\text{GWO-PID} = 1.4420 + \left(\frac{5.6598}{s}\right) + 0.0545s \qquad (21)$$

5. Proposed Hybrid GWO-PSO-PID Controller

The method suggested in this research is a new hybrid nature-inspired algorithm known as hybrid GWO-PSO, which combines PSO and GWO algorithms. The PSO and GWO methods coevolve and improve the search process by updating the position of the particles. It uses both variants simultaneously, making it coevolutionary. Because two different approaches produce the final solutions to the problems, it is mixed. The capacity to explore in GWO and exploit in PSO to generate the strengths of both types is enhanced by this update. The recommended algorithm flowchart is displayed in Figure 5. The flowchart of the hybrid GWO-PSO algorithm describe as per following steps:

Step 1: *Initialization*

- Define PID parameters (K_P, K_I, K_D) with their lower and upper bounds (lb=0 and ub=10).
- Set up a population of wolves (N=10) in the search space with arbitrary locations and movements.
- Set parameters for PSO: Inertia weight (ω = 0.5), Acceleration constants ($c_1 = c_2 = c_3$ =1.5)
- Set parameters for GWO: Convergence factor (a = 2 - t/k_{max}).
- Define number of Iterations (k=20).

Step 2: Evaluate initial population

- Determine each particle's fitness by applying the specified objective function (IAE).
- Using their fitness scores, identify the best three wolves (α, β, and δ).

Step 3: Main Optimization Loop

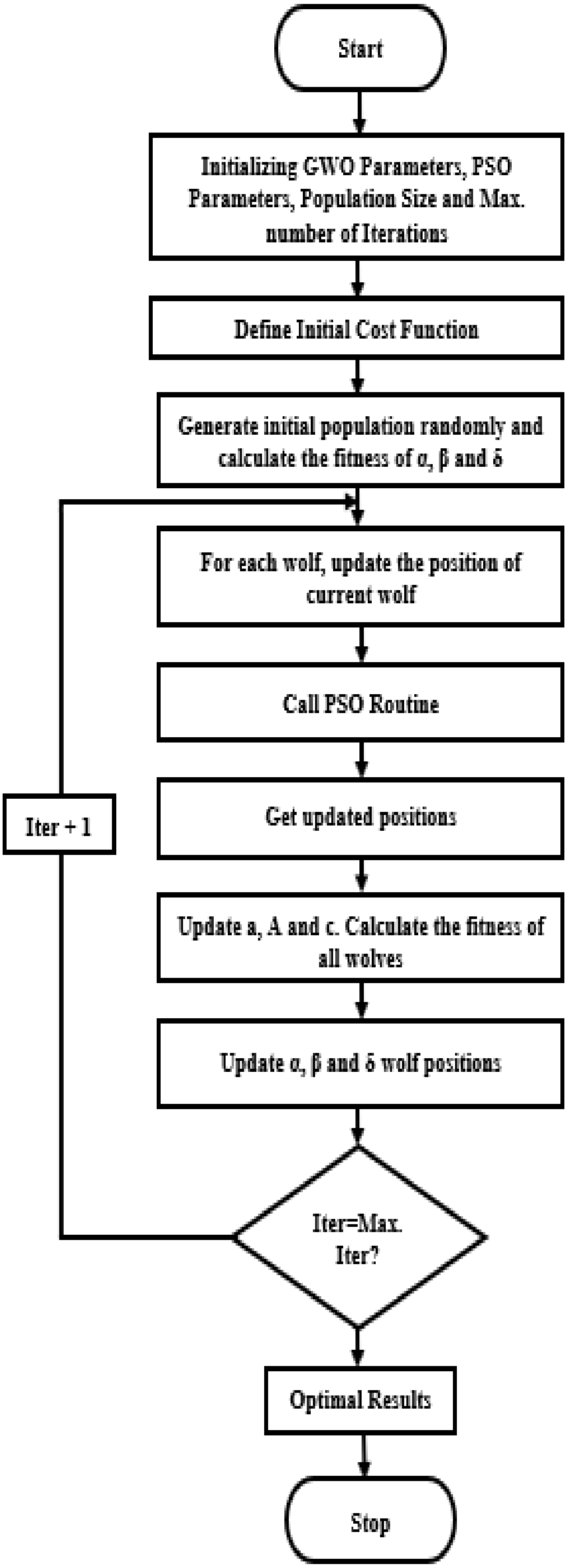

Figure 5. Flowchart of Hybrid GWO-PSO Algorithm

5.1 GWO Update

- Update the positions of particles using equations (22) to (24) represent the core position update mechanism of the GWO algorithm, modeling the leadership hierarchy and hunting strategy of grey wolves in nature. Each grey wolf updates its position based on the three leading wolves: α, β, and δ which represent the best, second-best, and third-best solutions, respectively.

$$\overrightarrow{D_\alpha} = |\,(c_1\,\overrightarrow{X_\alpha}\,) - (\omega\ \overrightarrow{X}\,)|, \text{ and } \overrightarrow{X_1} = |\,\overrightarrow{X_\alpha} - (a_1\,\overrightarrow{D_\alpha})\,|, \quad (22)$$

$$\overrightarrow{D_\beta} = |\,(c_2\,\overrightarrow{X_\beta}) - (\omega\ \overrightarrow{X})\,|, \text{ and } \overrightarrow{X_2} = |\,\overrightarrow{X_\beta} - (a_2\,\overrightarrow{D_\beta}\,)|, \quad (23)$$

$$\overrightarrow{D_\delta} = |\,(c_3\,\overrightarrow{X_\delta}\,) - (\omega\ \overrightarrow{X})\,|, \text{ and } \overrightarrow{X_3} = |\,\overrightarrow{X_\delta} - (a_3\,\overrightarrow{D_\delta}\,)|. \quad (24)$$

Here, $\overrightarrow{X}$ is the current position of the search agent, $\overrightarrow{X_\alpha}, \overrightarrow{X_\beta}, \overrightarrow{X_\delta}$ are the positions of the top three solutions, and weights c_1, c_2, c_3 control the importance of each wolf, while ω manages the influence of inertia. a_1, a_2, a_3 are convergence factor. The inertia constant (ω) is utilized to regulate the grey wolves balance between exploration and exploitation within the search space, replacing traditional mathematical formulas. By using equation (20), update position of each particle by checking the average influence of α, β, δ. The novelty of the hybrid GWO-PSO algorithm lies in the integration of PSO inspired elements, particularly the inertia weight term $(\omega\,\overrightarrow{X})$ and velocity-based exploration mechanics into the classical GWO equations. Unlike traditional GWO, where only position updates are governed by a leader-based hierarchy, the inclusion of an inertia-like term introduces momentum**,** enabling agents to retain useful search directionality from previous iterations. This bridge the exploration power of GWO with the refined convergence behavior of PSO, potentially improving convergence speed and solution quality.

5.2 PSO Update

- Use the PSO modified velocity using equation (25) and update the particle velocities.

$$v_i^{k+1} = \omega\{v_i^k + c_1 r_1\left(x_1 - x_i^k\right) + c_2 r_2(x_2 - x_i^k) + c_3 r_3(x_3 - x_i^k)\} \quad (25)$$

Where,

v_i^{k+1} new velocity of particle ′i′ at iteration $k + 1$, ω is inertia weight use to controls how much of the previous velocity is retained, v_i^k is the current velocity of particle ‘i’ at iteration k, c_1,c_2,c_3 are acceleration coefficients control how much the particle is attracted to the best solutions, r_1,r_2,r_3 are random numbers between 0 and 1 helping avoid local minima, the product of c and r represent the pull towards the top 3 wolves, x_i^k is current position of particle ‘i’, x_1 is alpha (best solution), x_2 is beta (second-best), x_3 is delta (third-best). For an efficient search, equation (25) integrates the influence of

GWO and the velocity update method of PSO. Then update each particle's position using its new velocity from equation (15) to its current position.

5.3 Fitness Evaluation

- Calculate the fitness of all updated particles using the objective function (IAE).
- Update α, β, and δ based on the new fitness values.

5.4 Update Parameters

- As the iterations continue, dynamically modify the control parameters (ω, c_1, c_2, c_3, and a) to balance between exploration and exploitation.

Step 4: Repeat steps 3(a) through 3(d) until the final repetition is reached.

Step 5: Provide the ideal PID parameters as the position of the best particle (α).

Figure 6 shows the convergence graph of hybrid controller. Utilizing the hybrid GWO-PSO method with the IAE as the objective function, PID parameters for brushless PMDC motor control were determined. The hybrid GWO-PSO-PID controller was then designed utilizing these values, as illustrated in equation (26).

$$\text{Hybrid GWO-PSO-PID} = 2.7725 + \left(\frac{1.4992}{s}\right) + 0.0759s \qquad (26)$$

6. Results and Discussion

In this work MATLAB R2017b software with fixed-step and variable-step solvers supported in Simulink, windows 10, intel core i5 processor, 8 GB RAM, SSD storage are used. The PID controllers designed in Sections 4 and 5 are tested based on the criteria outlined in this section for brushless PMDC motor used for drone applications using MATLAB/Simulink.

The findings show that the hybrid GWO-PSO controller outperforms ZN, GA, PSO, and GWO techniques, displaying improved responsiveness and precision in PMDC motor performance. By effectively addressing the complexities of drone motor as mention in Section 2, the hybrid GWO-PSO controller demonstrates a significant advantage, highlighting its effectiveness in real-world applications.

6.1 Closed-loop Response of Controllers

Table 2 shows the time response specifications of brushless PMDC motor control using controllers. The results clearly demonstrate the superior performance of the Hybrid GWO-PSO-PID controller across all evaluated parameters. While the ZN-PID method exhibits the fastest rise time of 0.0067 s, it suffers from excessive peak overshoot (80.91%) and the highest IAE (0.1184), indicating poor stability and control accuracy.

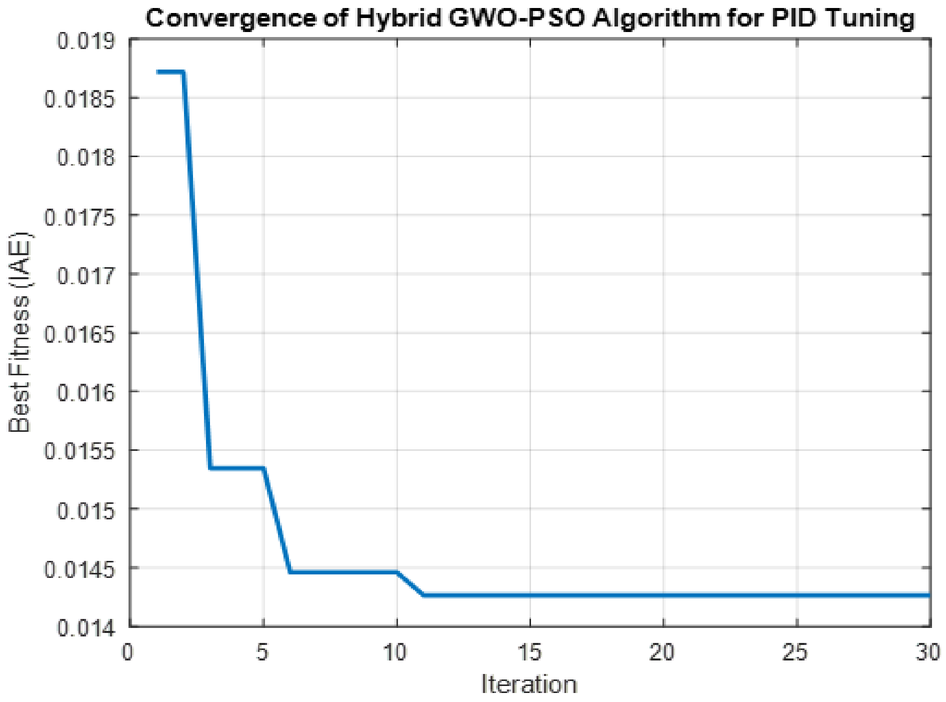

Figure 6. Convergence graph of Hybrid GWO-PSO-PID controller for Brushless PMDC Motor

Table 2. Time Domain Specifications with IAE objective function

Controllers	Rise Time, Tr (s)	Settling Time, Ts (s)	Peak Overshoot, Mp (%)	IAE
ZN-PID	0.0067	1	80.91	0.1184
GA-PID	0.086	0.7	15.698	0.0391
PSO-PID	0.184	0.5	3	0.0307
GWO-PID	0.073	0.453	1.531	0.0152
Hybrid GWO-PSO-PID	0.055	0.192	0.442	0.0143

Table 3. Time Domain Specifications with ITAE objective function

Controllers	Settling Time, Ts (s)	Peak Overshoot, Mp (%)	ITAE
GA-PID	3.75	6.98	0.1524
PSO-PID	2.14	2.58	0.0856
GWO-PID	0.54	0.51	0.0402
Hybrid GWO-PSO-PID	0.32	0.43	0.0267

Table 4. Time Domain Specifications with ISE objective function.

Controllers	Settling Time, Ts (s)	Peak Overshoot, Mp (%)	ISE
GA-PID	3	2.58	0.0473
PSO-PID	1.25	1.73	0.0156
GWO-PID	0.63	0.61	0.0119
Hybrid GWO-PSO-PID	0.23	0.54	0.0017

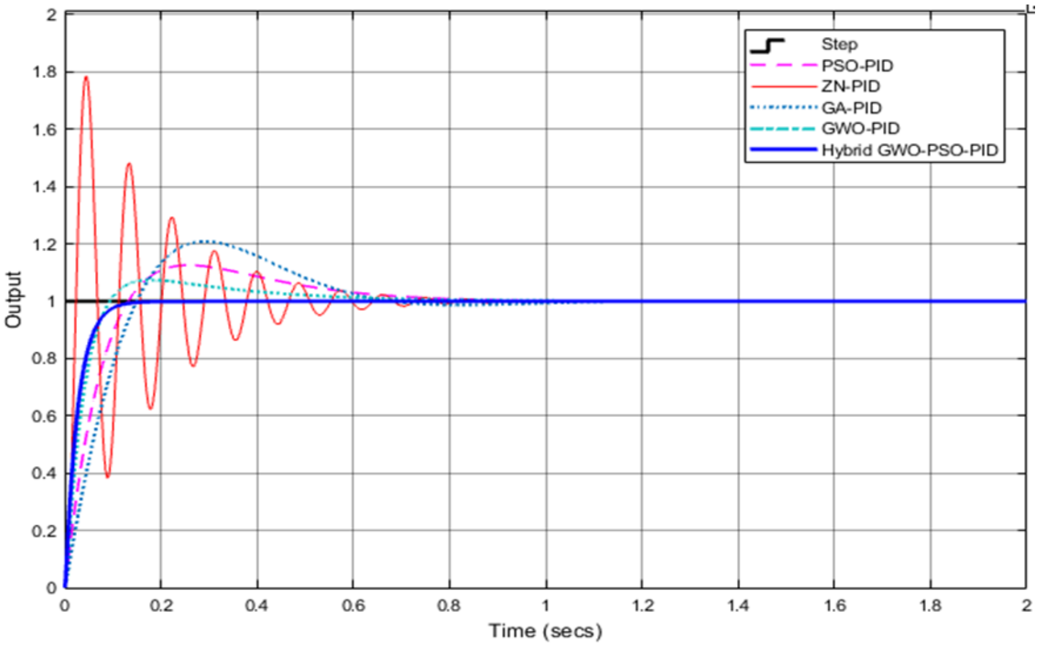

Figure 7. Close-loop Response of Controller for Brushless PMDC Motor

In contrast, the Hybrid GWO-PSO-PID controller achieves a balanced performance with a rise time of 0.055 s, a significantly reduced settling time of 0.192s (80.8% improvement over ZN), and minimal overshoot of 0.442%—a dramatic 99.45% reduction compared to ZN. Moreover, it records the lowest IAE value of 0.0143, marking an 87.9% improvement over the ZN-PID, and also better perform over individual GA-PID (0.0391), PSO-PID (0.0307), and GWO-PID (0.0152). These numerical results indicate that integrating the exploration ability of GWO with the exploitation strength of PSO leads to a more robust and accurate PID tuning strategy for PMDC motor control.

Table 3 and 4 shows comparative analysis between settling time and overshoot of brushless PMDC motor PID control system with ITAE and ISE objective function. This system is very quick means rise time in all criterion almost same. ZN provides PID parameters heuristically, not by minimizing an objective function like GA, PSO, or GWO. The Hybrid GWO-PSO-PID tuning strategy demonstrates superior performance across all key metrics — fastest response, minimal overshoot, and lowest error indices (ITAE and ISE).

The closed-loop response of system with IAE objective function shown in Figure 7, highlights the better performance of the proposed Hybrid GWO-PSO-PID controller. While the ZN-PID controller shows a highly oscillatory response with a large peak overshoot and a long settling time. The proposed hybrid controller achieves a smooth, fast, and stable response with minimal overshoot and a quick settling time. Compared to GA-PID and PSO-PID, which exhibit overshoots of 15.698% and 3% respectively [36], the hybrid method demonstrates significantly improved damping and convergence. GWO-PID performs better than GA and PSO, yet still falls short of the hybrid approach. This comparative analysis clearly illustrates the effectiveness of the hybrid algorithm in delivering optimal PID tuning for brushless PMDC motor control.

6.2 Hybrid GWO-PSO-PID Controller Response for Disturbance

In disturbed system, the response of hybrid controller obtained is shown in Figure 8. When disturbances are introduced at 1.5s and 2.5s with amplitude 2, the hybrid controller exhibits rapid recovery with minimum deviations, and returning quickly to its steady-state value. Thus, this is highly applicable in areas requiring precision and adaptability, such as drone control for smooth flight and efficient energy use, industrial automation for robotic systems.

6.3 Robustness of Hybrid GWO-PSO-PID Controller

The effect of parametric uncertainty on a brushless PMDC motor response under various hybrid GWO-PSO-PID controller variation levels (±10%, ±5%, and 0%) by considering IAE objective function is depicted in Figure 9. The zoomed-in section highlights the transient response sensitivity to parameter changes, showing that clear parameter variations, result in a slightly slower rise time and minor deviations in the response amplitude. Despite these variations, the system maintains stability and quickly converges to the steady state, indicating robustness against moderate parametric uncertainties.

6.4 Speed Control of Brushless PMDC Motor using MATLAB Simulation

Figure 10 illustrates real time MATLAB simulation speed control system for brushless PMDC motor using a feedback control loop as shown in Figure 4. PID controller processes error to produce a duty cycle for the PWM generator, which drives the motor through a universal bridge (inverter). The motor rotor speed, stator currents, and electromagnetic torque are measured and fed back into the system. The decoder processes signals from the motor for rotor position detection, ensuring proper commutation and speed regulation. This closed-loop system ensures precise and stable motor speed control [28, 29].

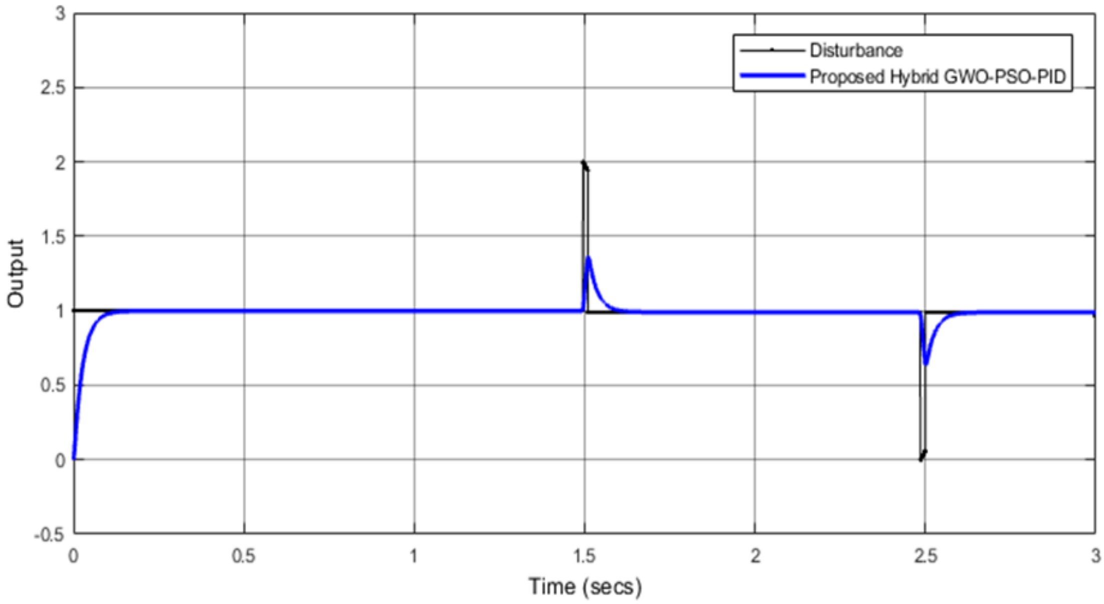

Figure 8. Hybrid GWO-PSO-PID Controller Response with Disturbance

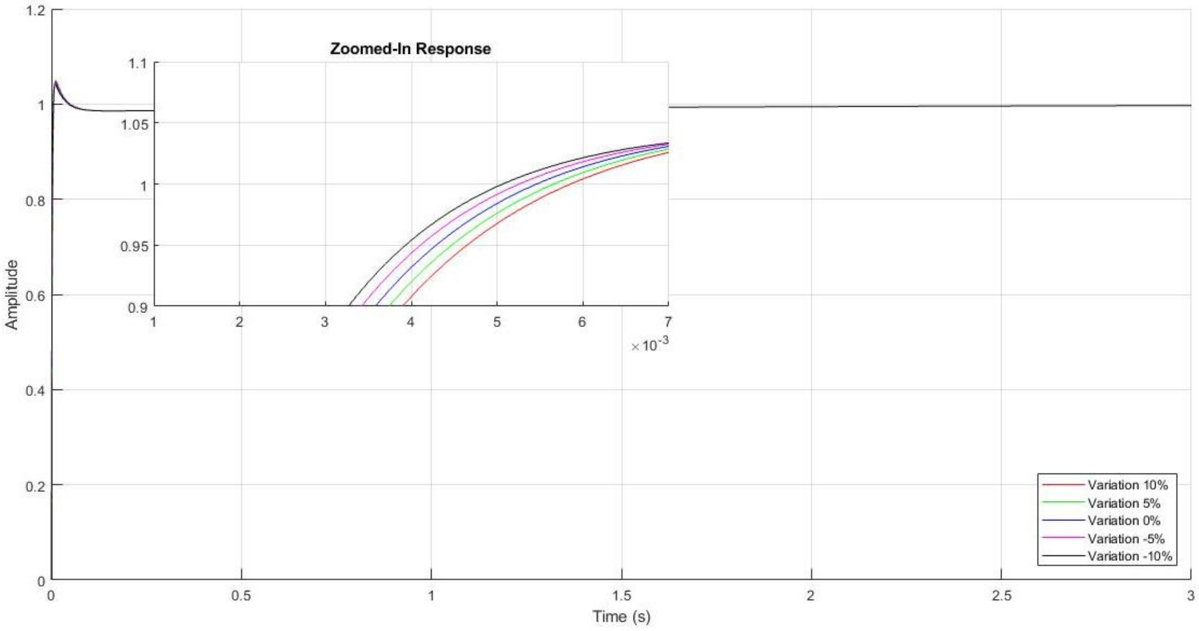

Figure 9. Hybrid GWO-PSO-PID Response with Parametric Uncertainty

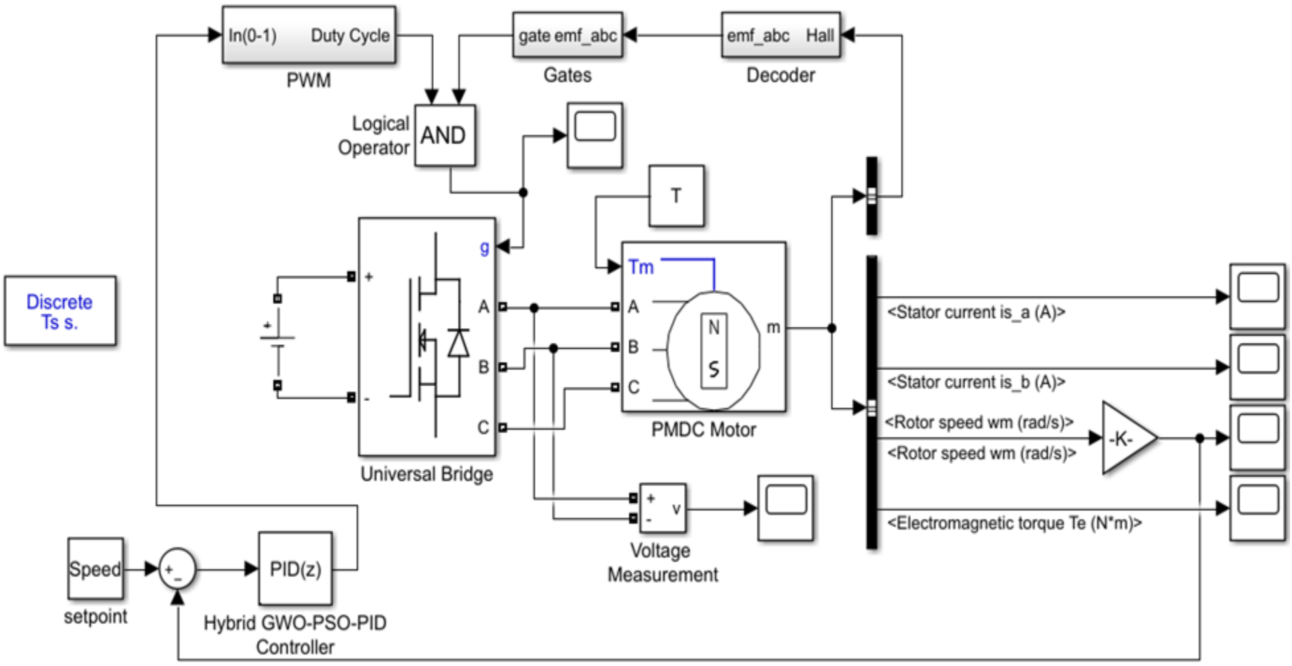

Figure 10. Simulink circuit for PMDC Motor with PID Controller

Figure 11 presents the speed control response of a brushless PMDC motor with 0.2Nm load torque using various PID tuning methods. The speed response plot compares different PID tuning methods for a motor targeting 1000 RPM, showing that the Hybrid GWO-PSO-PID controller outperforms all others with the fastest settling time (0.6sec), minimal overshoot (1025 RPM), and stable convergence. In contrast, the ZN-PID exhibits the highest overshoot (1650RPM), deep undershoot (600RPM), and the slowest settling (1.2 sec), indicating poor damping. The GA-PID, PSO-PID, and GWO-PID offer improved performance over ZN-PID with reduced oscillations and faster convergence, but still fall short of the hybrid method. Overall, the hybrid controller demonstrates superior speed regulation and stability, making it ideal for precision control applications.

6.5 Reference Trajectory Response of Controllers

Figure 12 illustrates the reference tracking or set-point tracking of PID controllers for brushless PMDC motor control.

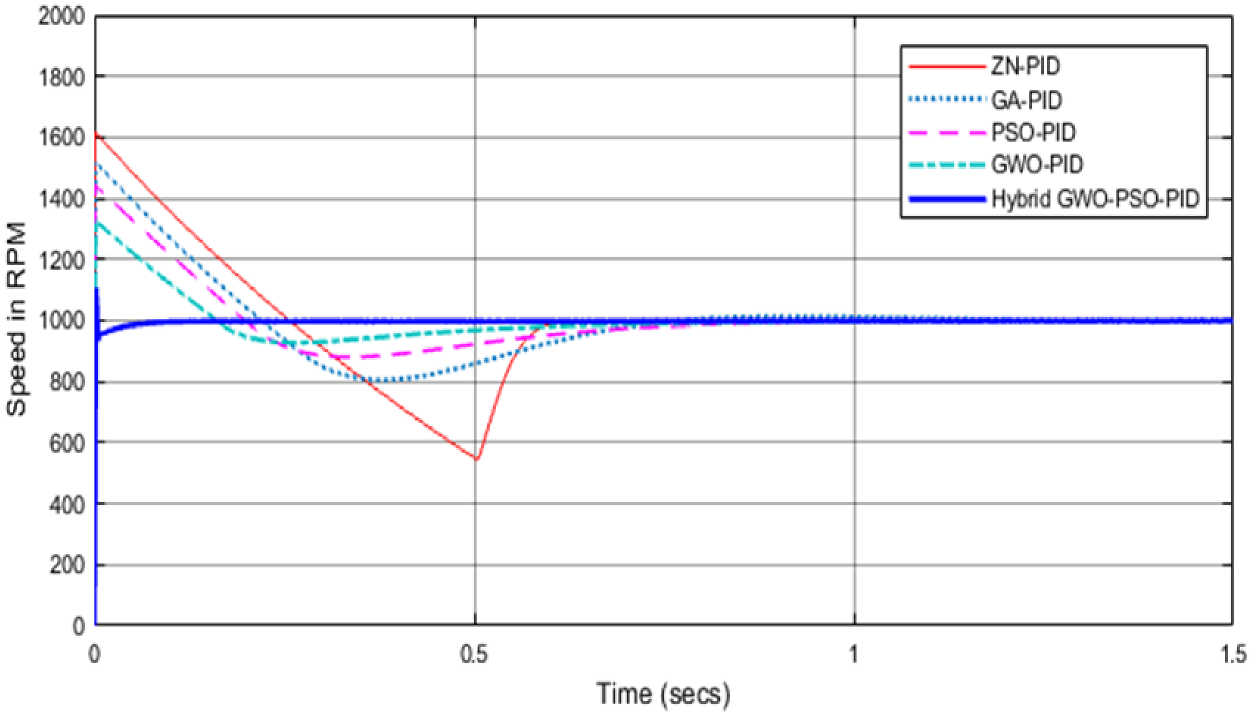

Figure 11. Speed Control of Brushless PMDC Motor with TL=0.2Nm

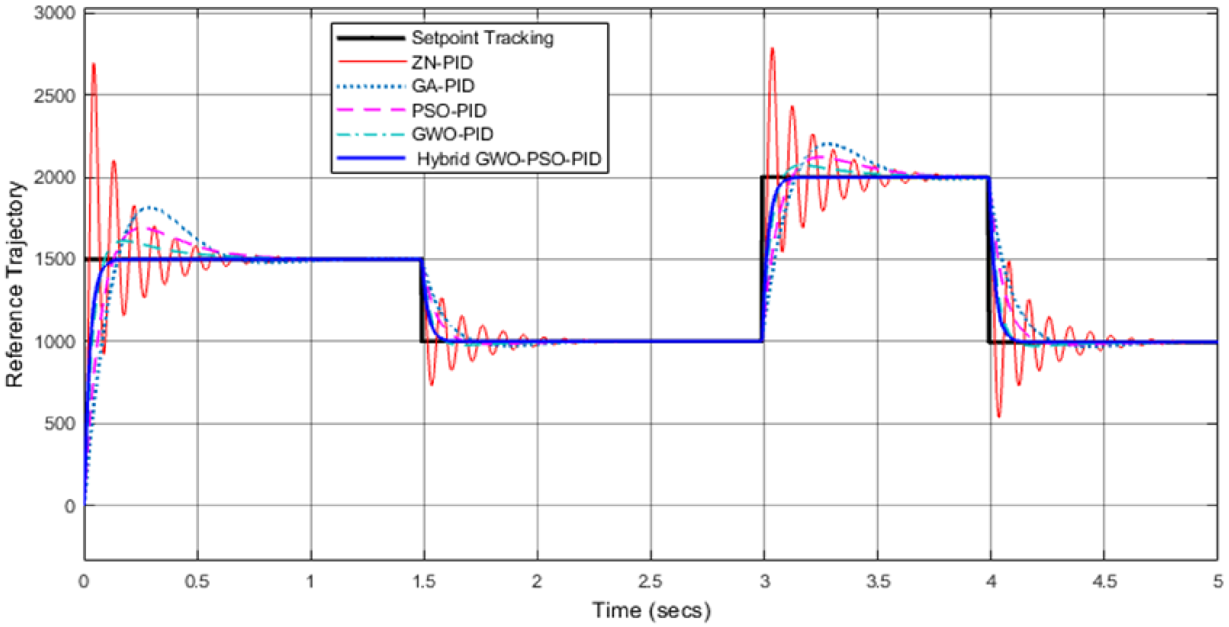

Figure 12. Reference Trajectory of Controllers for Brushless PMDC Motor Control

Assume speed of motor changes 1500rpm to 1000rpm at 1.5s, 1000rpm to 2000rpm at 3s and 2000rpm to 1000rpm at 4s. At each change, ZN-PID exhibits high overshoot, significant oscillations and required 1s to settle down [30]. It shows poor tracking performance. On the other hand, GA-PID, PSO-PID, and GWO-PID improve the tracking accuracy with reduced overshoot and settling time [31, 32, 34]. But hybrid GWO-PSO-PID response shows exceptional performance in motor control, closely aligning with the reference trajectory while exhibiting negligible overshoot and minimal deviations.

6.6 Torque and Speed Responses of Brushless PMDC Motor

Figures 13 (a) and (b) illustrate the motor speed and torque response under the hybrid controller when subjected to load torques of 1 Nm and 10 Nm, respectively. In a PMDC motor, load torque represents the force required to counteract the resistance from the connected load, which includes friction, gravity, and other opposing forces. This resistance must be overcome to rotate the shaft and achieve the motor's intended function [26, 27].

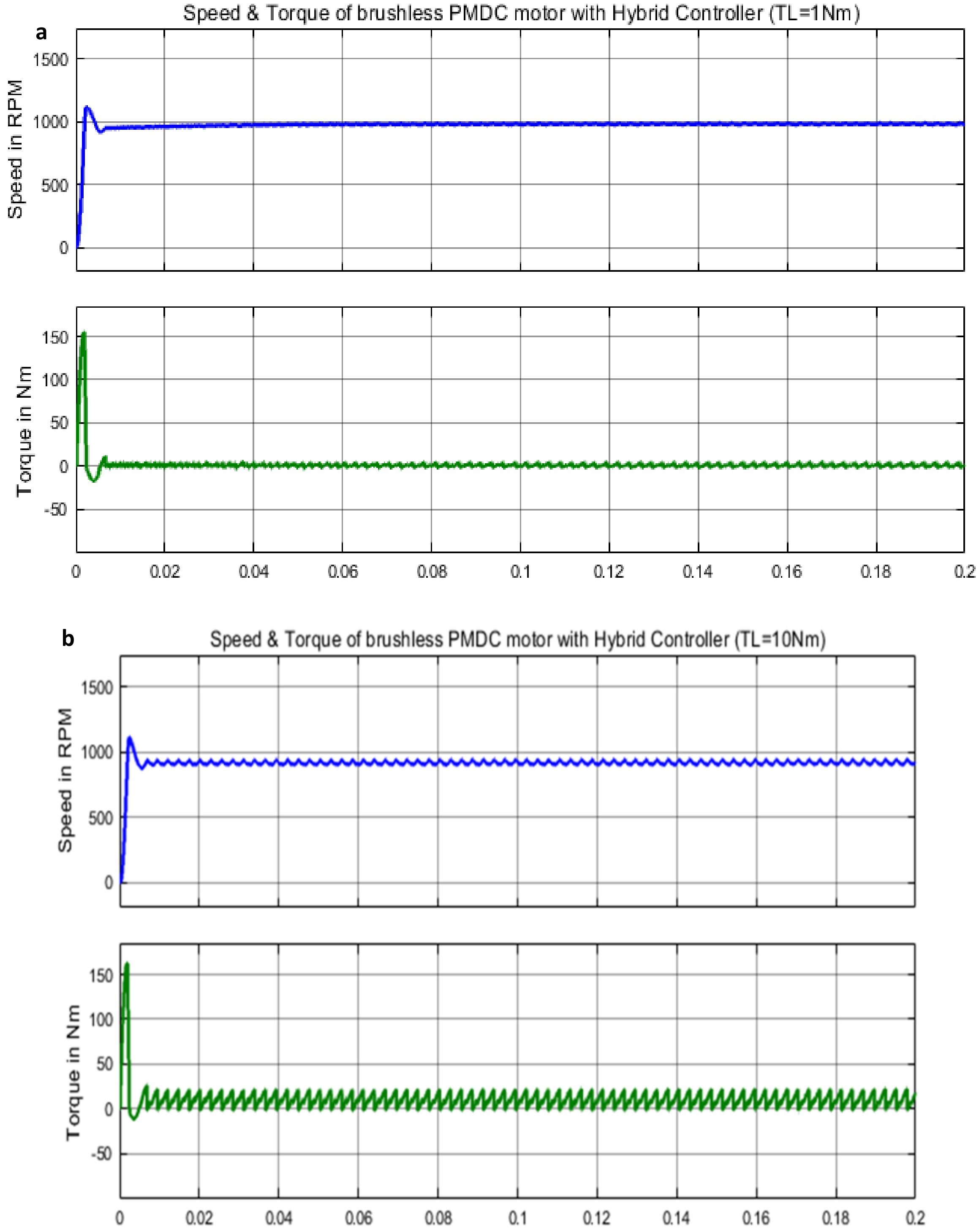

Figure 13. Speed and Torque Responses of Brushless PMDC Motor (a) TL=1Nm (b) TL=10Nm

As the load torque increases from 1 Nm to 10 Nm, the motor's speed decreases since the opposing force grows stronger. At lower speeds, PMDC motors generate higher torque, making them well-suited for applications that demand substantial starting torque. However, as the speed increases, torque gradually declines, eventually reaching a limit where the motor is no longer capable of sustaining the required torque to drive the load. Therefore, selecting an appropriate PMDC motor involves considering the expected load torque to ensure it delivers sufficient power for the desired application.

The results obtained are summaries that the hybrid GWO-PSO-PID controller efficiently handles the nonlinear characteristics of brushless PMDC motors in speed regulation. These motors exhibit nonlinear behavior due to factors like back-EMF fluctuations, varying loads, and dynamic operating conditions. By optimizing PID parameters, the hybrid controller ensures accurate speed control, improved stability, and enhanced adaptability. As a result, it significantly enhances performance in applications such as drones, where it enables smooth flight and rapid response, and robotics, where it provides precise motion control and improved energy efficiency, even in demanding environments. But hybrid algorithm incurs higher computational cost compared to standalone GWO or PSO due to the dual update mechanisms for position and velocity. Although the Hybrid GWO-PSO-PID controller provides good simulation results, but in real-time implementation viability depends on resolving issues with computational complexity, execution time, resource limitations, and uncertainties in the actual world. For the controller to function well in real-time applications, careful design, optimization, and implementation are essential. The proposed controller optimization technique offers fast convergence speed by effectively combining GWO's global exploration with PSO's local exploitation capabilities. Its computational complexity is slightly higher than individual algorithms due to dual update mechanisms, but this is balanced by fewer iterations needed to reach optimal solutions. The method shows moderate parameter sensitivity, with performance influenced by factors like population size and learning coefficients.

7. Conclusion and Future Scope

This research presents nature-inspired optimization methods for tuning PID controllers used in the control of brushless PMDC motors. The work explores GA, PSO, and GWO in detail as individual solution methods. To achieve improved performance, a hybrid approach combining GWO and PSO, referred to as Hybrid GWO-PSO, was implemented and analyzed. Based on the results, the hybrid GWO-PSO-PID outperformed than ZN-PID, GA-PID, PSO-PID, and GWO-PID. Traditional method, ZN lead to overshoot and longer settling times, which are overcome by using nature-inspired techniques. GA, PSO, and GWO improve performance but hybrid GWO-PSO algorithm successfully optimizes the PID controller, improving time response parameters, tracking accuracy, and minimizing error-index. It is found to be the best optimization method for PID tuning due to its simplicity, accuracy, and efficiency. This approach can be extended to applications like drones and quadcopters, where precise control is essential. The scalability of the algorithm to highly nonlinear or multi-input multi-output (MIMO) systems has not been fully validated and may require additional computational resources or parameter tuning. Also, sensitivity to initial population distribution can influence convergence speed and result quality, which may impact consistency in real-time control applications. Future work on the hybrid GWO-PSO algorithm in PID tuning validate real-time performance and robustness under realistic operating conditions, the controller can be implemented on embedded platforms. Also, expanding the optimization to handle multiple objectives such as minimizing settling time, overshoot, and energy consumption using Pareto-based techniques could make the controller more adaptable to complex system requirements.

References

[1] M. Deepak, R. Aruldavid, R. Verma, K. Sathyasekar, A. Barnawi, C. Bharatiraja, L. Mihet-Popa, A Review of BLDC Motor: State of Art, Advanced Control Techniques, and Applications, IEEE Access, 10, (2022) 1-1. https://doi.org/10.1109/ACCESS.2022.3175011

[2] J. Chen, The Application of PID Control in DC Motor Control Systems, Applied and Computational Engineering, 81, (2024) 164-170. https://doi.org/10.54254/2755-2721/81/20241083

[3] I. Fajuke, A. Raji, Optimal tuning of PID controller for speed control of DC motor using equilibrium optimizer, Indonesian Journal of Electrical Engineering and Computer Science, 30(1), (2023) 89-101. http://doi.org/10.11591/ijeecs.v30.i1.pp89-101

[4] R.S. Patil, S.P. Jadhav, M.D. Patil, Review of Intelligent and Nature-Inspired Algorithms-Based Methods for Tuning PID Controllers in Industrial Applications, Journal of Robotics and Control (JRC), 5(2), (2024) 336-358. https://doi.org/10.18196/jrc.v5i2.20850

[5] R.P. Borase, D.K. Maghade, S.Y. Sondkar, S.N. Pawar. A review of PID control, tuning methods and applications. International Journal of Dynamics and Control, 9(2), (2021) 818-827.

[6] D.C. Meena, A. Devanshu, (2017) Genetic algorithm tuned PID controller for process control, 2017 International Conference on Inventive Systems and Control (ICISC), India. https://doi.org/10.1109/ICISC.2017.8068639

[7] M.A. Ibrahim, A.K. Mahmood, N.S. Sultan. Optimal PID controller of a brushless dc motor using genetic algorithm. International Journal of Power Electronics and Drive Systems (IJPEDS), 10(2), (2019) 822-830. http://doi.org/10.11591/ijpeds.v10.i2.pp822-830

[8] P.G. Medewar, R.K. Munje. (2015) PSO based PID controller tuning for PMDC motor. In 2015 International Conference on Energy Systems and Applications, IEEE, Pune, India. https://doi.org/10.1109/ICESA.2015.7503404

[9] M. Xu, Control of DC adjustable speed electric vehicle based on PSO-PID algorithm optimization research, 2022 IEEE 5th International Conference on Automation, Electronics and Electrical Engineering (AUTEEE), IEEE, Shenyang, China, (2022) 616-621. https://doi.org/10.1109/AUTEEE56487.2022.9994335

[10] G.S. Hocaoglu, N. Cavli, E. Kılıc, Y. Danayiyen. (2023) Nonlinear Convergence Factor Based Grey Wolf Optimization Algorithm and Load Frequency Control, in 5th Global Power, Energy and Communication Conference (GPECOM), IEEE, Turkiye.

https://doi.org/10.1109/GPECOM58364.2023.10175823

[11] A. Pawlowski, M. Ciezkowski, S. Romaniuk, Z. Kulesza, GWO-Based Multi-Stage Algorithm for PMDC Motor Parameter Estimation, Sensors, 23(11), (2023) 5047. https://doi.org/10.3390/s23115047

[12] A.K. Ali, An optimal design for an automatic voltage regulation system using a multivariable PID controller based on hybrid simulated annealing – white shark optimization, Scientific Reports, 14(1), (2024) 30218. https://doi.org/10.1038/s41598-024-79300-7

[13] K. Janprom, W. Permpoonsinsup, S. Wangnipparnto, Intelligent Tuning of PID Using Metaheuristic Optimization for Temperature and Relative Humidity Control of Comfortable Rooms, Journal of Control Science and Engineering, 2020(1), (2020) 2596549. https://doi.org/10.1155/2020/2596549

[14] V. Dubey, H. Goud, P.C. Sharma, Role of PID Control Techniques in Process Control System: A Review, in Data Engineering for Smart Systems, Proceedings of SSIC, 238, (2021) 659-670. https://doi.org/10.1007/978-981-16-2641-8_62

[15] M. Sreejeth, R. Kumar, N. Tripathi, P. Garg, (2023) Tuning A PID Controller using Metaheuristic Algorithms, 2023 8th International Conference on Communication and Electronics Systems (ICCES), IEEE, India. https://doi.org/10.1109/ICCES57224.2023.10192687

[16] S.B. Joseph, E.G. Dada, A. Abidemi, D.O. Oyewola, B.M. Khammas, Metaheuristic algorithms for PID controller parameters tuning: Review, approaches, and open problems, Heliyon, 8(5), (2022) e09399. https://doi.org/10.1016/j.heliyon.2022.e09399

[17] W.V. Jahnavi, J.N.C. Sekhar, A.S. Reddy, A Review on PID Controller Tuning Using Modern Computational Algorithms. Journal of Emerging Technologies and Innovative Research, 10(8), (2023) 160-168.

[18] Z. Wang, C. Qin, B. Wan, W.W. Song. A Comparative Study of Common Nature-Inspired Algorithms for Continuous Function Optimization. Entropy, 23(7), (2021) 874. https://doi.org/10.3390/e23070874

[19] H. Wang, K.T. Chau, W. Liu, S.M. Goetz, Design and Control of Wireless Permanent-Magnet Brushless DC Motors, IEEE Transactions on Energy Conversion, 38(4), (2023) 2969-2979. https://doi.org/10.1109/TEC.2023.3292178

[20] A.R. Bhavsar, S.V. Patil, (2018) Advance Speed Control Technique of Permanent Magnet Brushless DC Motor Drive Using MATLAB Simulation and FPGA Controller. 2018 International Conference on Smart Electric Drives and Power System (ICSEDPS), IEEE, India. https://doi.org/10.1109/ICSEDPS.2018.8536003

[21] P. Kumar, R.K. Behera, D.V. Bhaskar, (2018) Novel closed-loop speed control of permanent magnet brushless DC motor drive, 2018 Technologies for Smart-City Energy Security and Power (ICSESP), India. https://doi.org/10.1109/ICSESP.2018.8376725

[22] V. Sankardoss, P. Geethanjali, Parameter estimation and speed control of a PMDC motor used in wheelchair. Energy Procedia, 117, (2017), 345-352. https://doi.org/10.1016/j.egypro.2017.05.142

[23] S.W. Khubalkar, A.S. Chopade, A.S. Junghare, M.V. Aware, (2016) Design and tuning of fractional order PID controller for speed control of permanent magnet brushless DC motor. 2016 IEEE First International Conference on Control, Measurement and Instrumentation (CMI), IEEE, India, 326-320. https://doi.org/10.1109/CMI.2016.7413764

[24] S. Darvishpoor, A. Darvishpour, M. Escarcega, M. Hassanalian, Nature-Inspired Algorithms from Oceans to Space: A Comprehensive Review of Heuristic and Meta-Heuristic Optimization Algorithms and Their Potential Applications in Drones, Drones, 7(7), (2023) 427. https://doi.org/10.3390/drones7070427

[25] A. Mukhtar, P.M. Tiwari, S. Alotaibi, Optimal design of tilt integral derivative controller for a boost converter based on swarm-inspired algorithms, Scientific Reports, 15(1), (2025) 57. https://doi.org/10.1038/s41598-024-84088-7

[26] M.A. Ramya, S.P. Jadhav, S.N. Pawar, (2020) Design and Implementation of Particle Swarm Optimization (PSO) Tuned PID Controller for Speed Control of Permanent Magnet Brush Less DC (PMBLDC) Motor. In 2020 International Conference for Emerging Technology (INCET), IEEE, India. https://doi.org/10.1109/INCET49848.2020.9154039

[27] M. Mahmud, M.R. Islam, S.M.A. Motakabber, M.D.A. Satter, K.E. Afroz, A.A. Habib, (2022) Control Speed of BLDC Motor using PID. in 2022 IEEE 18th International Colloquium on Signal Processing and Applications (CSPA), IEEE, Malaysia. https://doi.org/10.1109/CSPA55076.2022.9782030

[28] L. Wang. (2020) Basics of PID Control, in PID Control System Design and Automatic Tuning using MATLAB/Simulink. https://doi.org/10.1002/9781119469414.ch1

[29] S. Oladipo, Y. Sun, Z. Wang, Optimization of PID Controller with Metaheuristic Algorithms for DC Motor Drives: Review, International Review of

Electrical Engineering (IREE), 15(5), (2020) 352-381. https://doi.org/10.15866/iree.v15i5.18688

[30] A. Banerjee, S. Bhattacharjee, B. Neogi, An application of Z-N Tuning method with PID controller to optimize the system performance of cardiac muscle model and its practical implementation using OP AMP. Journal of Mechanics of Continua and Mathematical Sciences, 14(3), (2019). https://doi.org/10.26782/jmcms.2019.06.00023

[31] A. Jayachitra, V. Rajendran. Genetic Algorithm Based PID Controller Tuning Approach for Continuous Stirred Tank Reactor. Advances in Artificial Intelligence, 2014(1), (2014) 791230. https://doi.org/10.1155/2014/791230

[32] A. Mukhtar, V.K. Tayal, H.P. Singh. (2019) PSO Optimized PID Controller Design for the Process Liquid Level Control. 2019 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), Noida, India. https://doi.org/10.1109/RDCAPE47089.2019.8979108

[33] V.P. Meena, U.K. Yadav, A. Gupta, V.P. Singh. (2022) Reduced-Order Model Based Design of PID Control for Zeta Converter Using GWO Algorithm, 2022 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), IEEE, India. https://doi.org/10.1109/PEDES56012.2022.10080587

[34] G. Phadke, S.Y. Bhuran, S. Das, Swarm PID: Enhancing Amphibious Robot Control through Partial Swarm Optimization. Journal of Electrical Systems, 20(3), (2024) 2783–2791. https://doi.org/10.52783/jes.4526

[35] N. Jain, G. Parmar, R. Gupta, I. Khanam, Performance evaluation of GWO/PID approach in control of ball hoop system with different objective functions and perturbation, Cogent Engineering, 5(1), (2018) 1465328. https://doi.org/10.1080/23311916.2018.1465328

[36] D. Mohanraj, R. Aruldavid, R. Verma, K. Sathiyasekar, A.B. Barnawi, B. Chokkalingam, L. Mihet-Popa, A review of BLDC motor: state of art, advanced control techniques, and applications. Ieee Access, 10, (2022) 54833-54869. https://doi.org/10.1109/ACCESS.2022.3175011

Authors Contribution Statement

Ramakant Patil: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Project Administration. Sharad Jadhav: Supervision, Conceptualization, Methodology, Analysis, Validation, Writing – Review & Editing, Resources. Machhindranath Patil: Validation, Resources, Writing – Review & Editing. All the authors approved the final version of this work.

Funding

The authors declare that no funds, grants or any other support were received during the preparation of this manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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?

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