LAUTECH Journal of Engineering and Technology 18 (4) 2024: 116-128
10.36108/laujet/4202.81.0421

An Approach Based on Firefly Algorithm for Optimal Tuning of Proportional-Integral-Derivative Controllers for Speed Control of DC Motor

[1]Adepoju G. A. and [2*]Salami H. O.

[1,2]Department of Electronic and Electrical Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomosho, Nigeria.

[1]gaadepoju@lautech.edu.ng, [2]salamihabeeb1@gmail.com

Article Info

Article history:

Received: Dec. 10, 2024
Revised: Jan. 14, 2025
Accepted: Jan. 17, 2025

Keywords:

Firefly Algorithm,
D.C Motors,
Speed Control,
Proportional Integral Derivative Controller,
Optimization,
Control Systems

Corresponding Author:
salamihabeeb1@gmail.com

ABSTRACT

This study presents an approach for optimal tuning of the parameters of the Proportional Integral Derivative (PID) controller for speed control of Direct Current (DC) motors using Firefly Algorithm (FA) to deliver efficient and accurate control of DC motors. Data for DC motors were sourced from Honey Well Flour Mills, Ilupeju, Lagos State, Nigeria, while its mathematical model was formulated using dynamic electric machine theory. MATLAB codes were written for the formulated model to simulate the open-loop response of the motor. Ziegler-Nichols (ZN) method was initially used to design the PID controller and named ZN-PID, while a firefly algorithm-tuned PID controller model was developed and named FA-PID. The performance evaluation of the FA-PID approach was carried out using rise time, setting time, mean squared error and overshoot as metrics. Simulation results indicate that at motor full speed, the rise time, settling time, overshoot and mean square error values for the ZN-PID tuned controller were 0.5000 s, 6.196 s, 22.94 % and 0.001415 $(rad/s)^2$, respectively, as compared to 0.0051 s, 0.0081 s, 0.0002 % and 0.000673 $(rad/s)^2$ obtained using FA-PID tuned controller. The results revealed that FA is a potent optimization technique for optimal tuning of PID controller parameters; hence, the developed FA-PID tuned controller can be used by machine operators in various industrial applications for controlling the speed of DC motors

INTRODUCTION

The use of prime movers continues to dominate across various industrial settings. Several types of prime movers such as steam, hydraulic and other types of engines are in existence; however, the most commonly used prime mover is the DC motor (Praboo and Bhaba, 2013). Due to their high reliability, flexibility and low cost, they are widely used in industrial applications, robot manipulators and home appliances where speed and position control of motor are required such as electric traction, golf carts, quarry and mining applications among others (Sankardoss and Geethanjali, 2017; Dursun and Durdu, 2016; Chao *et al*., 2019).

Speed control of a DC motor is the intentional change of the drive speed to a value required for performing the specific work process. Speed control differs from the concept of speed regulation where there is a natural change in speed due to a change in load on the shaft, it is done either manually by the operator or through some automatic control device (Dursun and Durdu, 2016; Hamida *et al.*, 2019).

Although, extensive studies have been carried out in designing high-performance motor drives, however, industrial applications are demanding more robust and higher-performance drives (Hashim and Ahmed, 2013). Of the various closed-loop controller designs available to date, the Proportional Integral

Derivative (PID) based control scheme is widely preferred in many industrial applications because of its simple structure and ease of realization (Kasilingam and Pasupuleti, 2015). Furthermore, the PID-based speed control scheme has many advantages such as less settling time, fast control and low cost (Sankardoss and Geethanjali, 2017; Hamida *et al.*, 2019; Hashim and Ahmed, 2013).

Different researchers have adopted several approaches for the optimal design of PID controller parameters. However, the speed response of the drive with PID controllers designed with the conventional techniques such as Ziegler-Nichol's frequency response method and Linear Quadratic Regulator (LQR) may be satisfactory but not necessarily be the best as they suffer mostly from high computational time and lengthy mathematical calculations (Tarei and Arora, 2017; Aspalli, 2017).

Kushwah and Patra (2014) presented weighted tuning methods of a PID speed controller for separately excited DC motors based on the Empirical Ziegler-Nichols tuning formula and modified Ziegler-Nichol PID tuning formula. Dantas *et al.* (2018) designed a PID controller for a vehicle DC motor with a separately excited field winding considering the field current constant using a controlled invariant set and multi-parametric programming concepts to consider the physical motor constraints as angular velocity and input armature voltage.

Singh *et al*. (2019) explored a comparative study of Ziegler-Nichols and Cohen-Coon methods in DC motor applications, highlighting their effectiveness and limitations in achieving desired speed control. Rahman *et al*. (2020) presented an approach based on the Ziegler-Nichols tuning method to DC motor speed control, comparing its performance with modern control strategies. The authors provide a detailed analysis of the step response and stability margins. Khushboo and Ranjan (2021) investigated the application of Cohen-Coon tuning for DC motor control, examining the effects of various controller settings on system response and stability.

In recent times, Artificial Intelligent (AI) based optimization techniques such as Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Equilibrium Optimizer (EO) among others have been reported to have performed excellently in tuning the PID controllers' parameters. Studies have shown that these techniques are capable of generating quality solutions due to ease of implementation, lesser computational time and fast convergence mobility (Dey *et al*., 2014; Kasilingam and Pasupuleti, 2015; Fajuke and Raji, 2021).

Devi and Biate (2016) presented a new Displacement-based Particle Swarm Optimization (DPSO) algorithm optimized PI controller for speed control of a DC Motor. Wati *et al*. (2019) presented the optimal tuning of fractional order PID controller for speed control of separately excited DC motor using a Genetic Algorithm. Islam *et al*. (2020) presented the control of a DC motor using a PID controller and fuzzy logic controller optimized using a Genetic Algorithm (GA).

Alsharif *et al*. (2023) explored a deep learning approach for optimal speed control of DC motors, utilizing neural networks for real-time performance adjustments. Sharma and Gupta (2022) presented the use of fuzzy logic in conjunction with genetic algorithms for enhancing the speed control of DC motors, providing adaptive control in varying conditions.

Ranjan *et al*. (2023) presented a hybrid model combining reinforcement learning with traditional control methods to achieve precise speed control in DC motors. Ali and Elhassan (2023) proposed a neural fuzzy inference system for effective speed control of DC motors, demonstrating improved stability and response time. Mahesh *et al*. (2023) focused on the use of machine learning algorithms, specifically support vector machines, for predictive speed control in DC motors under load variations.

In this study, an optimum PID controller for speed control of a separately excited DC motor is designed using the Firefly Algorithm (FA) optimization technique. Since its inception, FA has shown remarkable performances on a wide variety of optimization problems. The main advantage of FA over other swarm intelligent methods is its ease of implementation, followed by well-organized exploitation and exploration phases, and its very high efficiency in attaining global optimum solutions (Mandal and Kumar, 2017; Islam *et a*l., 2020).

Modeling and Operation of Direct Current Motor

A DC motor is comprised of three main parts, a current-carrying conductor called an armature, a circuit for a magnetic field provided by magnets of poles called a field system and a commutator that switches the direction of current in the armature as it passes a fixed point in space as illustrated in Figure 1 (Usoro *et al*., 2017: Abuzeid and Shtawa, 2014; Abut, 2016; Jambulingam, 2016; Adle and Rane, 2013; Mishra and Narain, 2013; Choudhary *et al*., 2014).

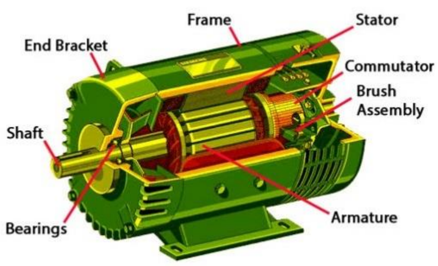

Figure 1. Pictorial representation of DC Motor (E.M.S., 2020)

The mathematical model of the electrical circuit of a separately excited DC motor can be obtained by applying Kirchoff's Voltage Law (KVL) to both armature circuit and field winding of the motor (Khan *et al*., 2015; Yadav and Tripathi, 2016).

$$V_a = i_a R_a + L_a \frac{di_a}{dt} + E_b \tag{1}$$

Armature voltage under steady-state conditions is given by Khan *et al*. (2013) and Bature *et al*. (2013) as;

$$V_a = E_b + i_a R_a \tag{2}$$

Back emf can be calculated using;

$$E_b = K\phi\omega_r = V_T - i_a R_a \tag{3}$$

where V_a represents the armature voltage, V_T is the source or terminal voltage, i_a is the armature current, R_a is the armature resistance, L_a is the self-inductance of the armature circuit, $\frac{di_a}{dt}$ is the rate of change of armature current with respect time, E_b is the generated back emf, K is the back emf constant and its value depend on the armature winding, ϕ is the flux per pole, ω_r is the speed of the motor in rad/sec. From equation (3), internally generated emf is directly proportional to the velocity of the motor. At a standstill, the motor speed is zero; therefore, back emf is also zero. The armature current at the starting is thus very large. Applying KVL in the field winding, the field voltage equation can be written as in (Tomar and Upadhyay, 2016);

$$V_f = i_f R_f + L_f \frac{di_f}{dt} \tag{4}$$

Field current is given by Sharma and Ashis (2015) as:

$$i_f = \frac{V_f}{R_f} \quad (5)$$

where V_f is the voltage applied to the field winding, i_f is the current through the field winding, R_f is the resistance of the field winding, L_f is the self-inductance of the field winding, and is the rate of change of field current concerning time.

The output motor torque can be estimated using (Sharma and Ashis, 2015; Kumar *et al*., 2014)

$$T_e = K_v i_a \quad (6)$$

From equation (6), the current in the armature winding is given as (Mickky and Tiwari, 2015);

$$i_a = \frac{T_e}{K_v} \quad (7)$$

Substituting for i_a in equation (3) and rearranging the terms

$$V_T - K\phi\omega_r = R_a\left(\frac{T_e}{K_v}\right) \quad (8)$$

Therefore, the torque developed in the rotor is;

$$T_e = \frac{K_v}{R_a}\left(V_T - K\phi\omega_r\right) \quad (9)$$

where T_e is the torque developed by the armature K_v is the torque constant

Equation (9) describes the relationship between the torque and speed of a separately excited DC motor. If the terminal voltage and flux are kept constant, the torque-speed relationship is a straight drooping line. Power developed by the armature is given by Prathibanandhi and Ramesh (2018) as;

$$P_a = E_b i_a \quad (10)$$

Substituting E_b in equation (3) to equation (10), the power developed by armature is given by Salim, (2015) as;

$$P_a = K\phi\omega_r i_a \quad (11)$$

Since ϕ is constant and assuming it is equal to 1;

$$P_a = K\omega_r i_a \quad (12)$$

Proportional Integral Derivative Controller

A proportional Integral Derivative controller is a generic control loop feedback mechanism (Bhatia *et al*., 2017; Dantas *et al*., 2018). The three main parameters involved are Proportional (P), which is responsible for the desired set point and adjusts the output controller, Integral (I), used to remove the steady-state error of the control system and improve the steady-state response, and Derivative (D), used in improving the transient response of the system respectively as shown in Figure 2 (Devi and Biate, 2016; Bhatia *et al*., 2017; Ahmed *et al*., 2013).

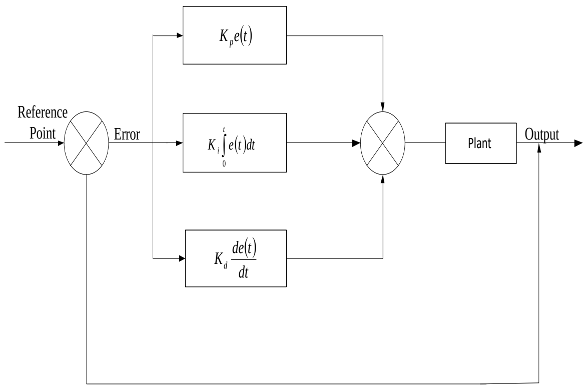

Figure 2. Basic Block Diagram of a Conventional PID Controller (Bhatia *et al*., 2017)

As illustrated in Figure 2, the variable $e(t)$ represents the tracking error which is the difference between the desired input value and the actual output. K_p, K_i, K_d are the proportional gain constant, the proportional integral gain and the derivative gain, respectively (Bhatia *et al*., 2017). To obtain the PID tuning parameters, it is desired to minimize a performance estimation function which is solved using the error criterion approach for Multi-Objective Problems (MOP). In these methods, the original MOP is converted to a Single-Objective Problem (SOP) and then solved by any of the deterministic or stochastic techniques (Hameed *et al*., 2016; Bhatia *et al*., 2017). These methods include Aggregating Functions (Weighted Sum Method and Global Criterion Method), Constraint Methods, Sequential Methods, Goal Attainment Method and Error Criterion Methods (Integrated Absolute Error (IAE), or the Integral of Squared Error (ISE), or the Integral of Time Weighted Squared Error (ITSE)) (Choudhary *et al*., 2014). However, for this study, the error criterion method is employed. This approach was chosen because it is simple in implementation and can be easily evaluated analytically in the frequency domain

Firefly Algorithm

The Firefly Algorithm is a contemporary meta-heuristic approach inspired by the flashing patterns of fireflies and their bioluminescent communication methods. Fireflies, which are winged beetles, emit light and blink during the night (Li and Kang, 2015). This light is produced chemically in their lower abdomen through a process known as bioluminescence. They utilize these light flashes primarily to attract mates and to signal potential dangers from predators (Yang and Deb, 2014; Li and Kang, 2015; Johari and Shamsuddin, 2013; Mandal and Kumar, 2017; Sarkar and Essam, 2016).

For a given medium with a fixed light absorption coefficient ‘γ’, the light intensity I varies with the distance ‘r’ (Mandal and Kumar, 2017; Li and Kang, 2015; Sarkar and Essam, 2016; Mirjalili, 2016).

$$\mathrm{I} = \mathrm{I}_0 \mathrm{e}^{-\gamma \mathrm{r}} \quad (13)$$

where I_0 is the original light intensity.

The attractiveness β of each firefly is given as (Sarkar and Essam, 2016):

$$\beta = \beta_0 e^{-\gamma r^2} \quad (14)$$

where β_0 is the attractiveness at r = 0.

For any two fireflies i and j situated at x_i and x_j, respectively, the distance $r_{i,j}$between them is given as;

$$r_{ij=}\left|x_i - x_j\right| = \sqrt{\sum_{k=1}^{d}\left(x_{i,k} - x_{j,k}\right)^2} \quad (15)$$

where $x_{i,k}$ is the k^{th} component of the spatial coordinate x_i and d is the distance between the coordinates; for $d=2$;

$$r_{ij} = \sqrt{\left(x_{i,1} - x_{j,1}\right)^2 + \left(x_{i,2} - x_{j,2}\right)^2} \quad (16)$$

In finding the optimal firefly in the population, the expression; $r_{ij} = G_{best}FV - P_{best}FV$ can be used to connect the distance between two fireflies. Where G_{best} represents the global optimal firefly, P_{best} represents the possible optimal firefly and FV is the fitness value assigned to each firefly in the population.

The movement of a firefly i, when attracted to another brighter firefly j than itself, is defined by the equation;

$$x_i = x_i + \beta_0 e^{-\gamma x}\left(x_j - x_i\right) + \propto (rand - 0.5) \quad (17)$$

where the first term of equation (17) is used to denote the current position of a firefly, the second term defines a firefly’s attractiveness to light intensity as seen by the adjacent firefly and the third term stands for the random movement of a firefly if no brighter firefly is left. The coefficient α is a randomization parameter and $rand$ is a random number generator uniformly distributed over the space [0, 1].

MATERIALS AND METHODS

This section presents the materials and methodology employed in this study. Integrated Absolute Error (IAE) operator technique of multi-objective optimization problem was employed to optimally tune the parameters of PID controller using Firefly Algorithm. The multi-objective optimization problem was converted to a single-objective optimization problem using the weighted average technique. The technique was chosen due to its straightforwardness and its flexibility in handling trade-offs among several objectives.

Three terms were added together, the first represents the integral term with gain K_i, the second is the proportional term with gain K_p and the third is the derivative term with gain K_d with an initial value of zero. The summing of the three terms gives the controller output as in equation (18) (Bhatia *et al*., 2017).

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (18)$$

The variable $e(t)$ represents the tracking error which is the difference between the desired input value and the actual output. K_p, K_i, K_d are the proportional gain constant, the proportional-integral gain and the derivative gain, respectively. The values of K_p, K_i, K_d obtained using ZN-PID are subsequently optimized using the firefly algorithm.

Optimization Model

A multi-objective solution method was employed to optimize the IAE as expressed in equation (19) by optimally tuning the parameters of the PID controller using the Firefly Algorithm. The IAE criterion is given according to Aspalli (2017):

$$\min IAE = \int_0^\infty |e| \cdot \partial t \quad (19)$$

Simplifying equation (19) further to reflect the various objectives using the weighted average technique;

$$\int_0^\infty |e| \cdot \partial t = \omega_1 (t_s) + \omega_2 (t_r) + \omega_3 (M_P) + \omega_4 \quad (20)$$

$$\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1 \quad (21)$$

By integrating equation (19), the MSE can be obtained as in equation (22);

$$MSE = \frac{1}{T} \int_0^T (e(t))^2 \partial t \quad (22)$$

where $\omega_1, \omega_2, \omega_3$ and ω_4 are the co-efficient representing the relative importance of the objective functions representing the setting time (t_s), rise time (t_r), maximum overshoot (M_P) and the Mean Squared Error (MSE) respectively, e is the difference between the reference speed and the actual speed, $e(t)$ represents the tracking error and T is a time constant.

Implementation of Firefly Algorithm for PID Parameter Tuning

For the optimization of PID controller parameters, Flashing lights were formulated based on the objective function of equation (19), taking the Integral of Absolute Error (IAE) as the fitness function. A script was written in MATLAB and named FA-PID, the script was used to implement the FA to iteratively improve the PID parameters. The control variables (proportional control, K_p, integral control, K_i and derivative control, K_d) which were adjusted for motor speed control are represented by a row vector Z which is mathematically modeled in equation (23).

$$Z = [Z_1, Z_2, Z_3] \quad (23)$$

At the inception stage, a population of fireflies (F_p) is generated and distributed evenly in a search medium and expressed using equation (24).

$$F_p = [F_1, F_2, F_3, F_{4,} .... F_M] \quad (24)$$

The parameters of FA such as the number of fireflies, number of parameters and attractiveness coefficient were all initiated. The velocity of an individual firefly is used to update its position based on the attraction to brighter fireflies (better solutions). The velocity can be represented as:

$$V_F = |V_{Kp}, V_{Ki,} V_{Kd}| \quad (25)$$

where V_{Kp} , V_{Ki} and V_{Kd} are the velocities corresponding to each PID parameter.

Each firefly represents a potential solution to the optimization problem and a fitness value is assigned to each firefly using equation (26).

$$F = \frac{1}{IAE} = \frac{1}{\int_0^{\infty} |e| \cdot \partial t} \quad (26)$$

The steps involved in the implementation of the FA approach for optimal tuning of the PID parameters are as follows;

Step 1: Read the DC motor data and ZN-PID controller parameters.

Step 2: Initialize the parameters and constants of the Firefly Algorithm such as α, β_0, λ and a maximum number of iterations.

Step 3: Generate randomly ‘n’ number of fireflies and set iteration count to 1.

Step 4: Evaluate the fitness value of each firefly using equation (26)

Step 5: Obtain the P_{best} values for all the fireflies and the best value among all the P_{best} values is identified as G_{best}.

Step 6: Determine the distance of attraction of each firefly.

Step 7: Calculate new P_{best} values for all the fireflies

Step 8: Update the position and velocity of the fireflies

Step 9: Calculate new fitness values for the updated positions of all the fireflies. If the new fitness value for any firefly is better than the previous P_{best} value then the P_{best} value for that Firefly is set to present fitness value. Similarly, the G_{best} value is identified from the latest P_{best} values.

Step 10: The iteration count is increased and if the iteration count has not reached maximum and convergence is not achieved, then go to step 3.

Step 11: Rank the Fireflies according to the current global best. G_{best} Firefly gives the minimized IAE and the results are printed.

SIMULATION RESULTS

This section presents and discusses the simulation results. The tests were carried out on the DC motor at no-load condition, as well as the loading condition using both the conventional Ziegler PID control method and the proposed FA-PID controller model. The specifications of the DC motor utilized in this study are detailed in Table 1.

The motor speed was increased momentarily in steps from 20 % to 100 %. At each speed setting, both the Ziegler-Nichols (ZN) and FA-PID controllers’ methods were applied to evaluate the motor under different loading conditions.

Table 1. DC Motor Specification

D.C Motor Parameter	Value
Motor Rating	3.5 HP
Supply Voltage	230 V
Rated Current	4.5A
Armature Resistance	5.5 Ω
Armature Inductance	0.50kgm/H
Inertia Constant	0.05kgms2/rad
Damping Constant	0.05gms2/rad
Torque Constant	0.25Vs/rad
Back Emf Constant	0.25kgm/V
Speed	1950 rpm

One effective approach for tuning PID controllers, as indicated by Ziegler-Nichols, involves using the no-load condition of the motor. The no-load response of the motor is represented as a unit step function graph, shown in Figure 3.

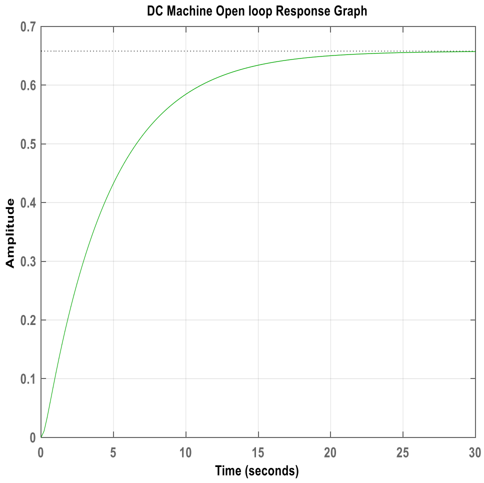

Figure 3. No-load Response of DC motor

During the loading condition, the conventional ZN-PID method was employed to regulate the motor's speed. Table 2 presents the various input parameters utilized for implementing the ZN-tuned PID controller across different speed conditions. The results of the simulation in terms of rise time, settling time, overshoot and mean squared error for the ZN-PID approach are presented in Table 3.

Table 2. ZN-PID Controller Parameters at Different Load Conditions

	S/N	Speed	Kp	Ki	Kd
ZN-PID	1	20	2.808	2.1907	0.877
	2	40	2.61	2.05	0.68
	3	60	2.504	1.903	0.64
	4	80	2.495	1.765	0.601
	5	100	2.487	1.752	0.585

Table 3. Results of Performance Metrics for ZN-PID

		Performance Metrics			
S/N	Speed (%)	Rise time (s)	Settling time (s)	Overshoots (%)	Mean Square Error (rad/s)
1	20	0.5922	7.328	26.43	0.007182
2	40	0.5636	7.053	25.50	0.005548
3	60	0.5401	6.826	23.73	0.003167
4	80	0.5300	6.205	23.01	0.001536
5	100	0.5000	6.196	22.94	0.001415

Simulation results indicate that the Ziegler-Nichols (ZN) PID controller method produces a significant oscillatory response under loading conditions when applied to the motor. This observation suggests that the PID parameters are not optimally tuned for direct application to the DC motor. Consequently, a structured optimization approach is essential to identify better parameter values, which, when applied to the system, can achieve near-perfect performance and enhanced robustness. The parameters derived from the Ziegler-Nichols tuned controller were utilized as boundary limits for optimizing the populations of the FA-PID controller method. Table 4 presents the outcomes from the FA-PID parameter tuning.

Table 4. FA-PID Controller Parameters at Different Load Conditions

	S/N	Speed	Kp	Ki	Kd
FA-PID	1	1	2.765	1.64	0.41
	2	2	2.52	1.53	0.361
	3	3	2.306	1.41	0.304
	4	4	2.284	1.21	0.281
	5	5	2.280	1.18	0.277

These optimized parameters were then applied to assess the response of the motor under varying loading conditions to evaluate its response and highlight the effectiveness of the FA-PID controller model. The results of the simulation in terms of rise time, settling time, overshoot and mean squared error for the FA-PID approach are presented in Table 5.

Simulation results indicate that the FA-PID tuned controller produces a lesser oscillatory response under different loading conditions when applied to the motor when compared to the ZN-PID approach as illustrated using Figure 4. This can be attributed to the optimal parameter tuning provided by the Firefly Algorithm. The result of Table 5 indicates that the FA-PID approach yields superior results in terms of rise and settling times, mean squared error, and overshoot as compared to the results of the ZN-PID approach presented in Table 4.

Table 5. Results of Performance Metrics for FA-PID

	Performance Metrics				
S/N	Speed (%)	Rise time (s)	Settling time (s)	Overshoots (%)	Mean Square Error (rad/s)
1	20	0.0063	0.0120	0.0007	0.001796
2	40	0.0060	0.0106	0.0006	0.001176
3	60	0.0058	0.0097	0.0005	0.000938
4	80	0.0054	0.0086	0.0003	0.000694
5	100	0.0051	0.0081	0.0002	0.000673

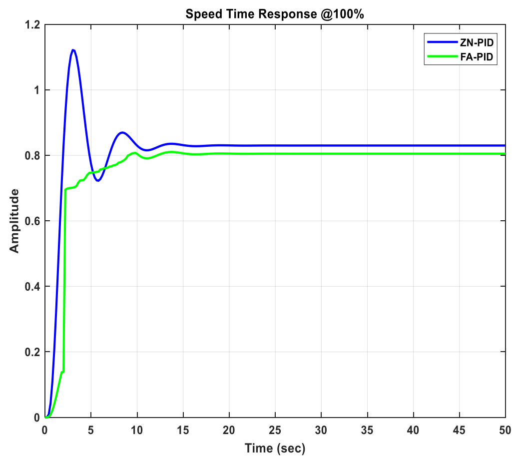

Figure 4. Speed Response Graph Comparison of FA-PID and ZN-PID Controller at 100%

As such, it is evident that the developed FA-PID controller model outperformed the conventional ZN-PID controller technique for speed control of DC motors.

CONCLUSION

Controlling the speed of DC motors is critical for various industrial applications. This study investigated the application of the Firefly Algorithm as an efficient optimization technique for optimal tuning of PID controller parameters. Specifically, the study addressed the challenge of identifying optimal PID parameters tuning that can lead to superior transient and steady-state performance compared to conventional tuning methods such as ZN and Cohen Coon. The implementation of the Firefly Algorithm for PID tuning resulted in significant improvements in key performance metrics, including reduced rise time, settling time, and overshoot compared to the conventional ZN approach. Also, the FA-PID tuned controller exhibited greater stability, effectively minimizing oscillations, providing smoother response during transient conditions and robust performance across a range of loading conditions. The findings from this study showed that the FA-PID controller offers improved system stability under varying load conditions, contributing to industry standards and encouraging further research into nature-inspired optimization techniques in control theory.

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