FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 38, Nº 2, June 2025, pp. 187 - 208
https://doi.org/10.2298/FUEE2502187P

Original scientific paper

OPTIMIZING FRACTIONAL ORDER PID CONTROLLER FOR DC MOTOR SPEED CONTROL USING ARTIFICIAL HUMMINGBIRD ALGORITHM

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Abstract. *This study implements the artificial hummingbird algorithm (AHA) to tune the FOPID controller optimally for DC motor speed control. The AHA algorithm is a straightforward and efficient method that mathematically simulates the foraging strategies of hummingbirds. It has been specifically designed to tackle a wide range of optimisation challenges. For a fair comparison, the proposed AHA-FOPID controller is tuned using the ITAE objective function and evaluated alongside the controllers optimized through GWO, PSO, and DE in the previous researches. Additionally, transient response analysis and load disturbance analysis are conducted. The suggested controller exhibits exceptional transient performance, as seen by a settling time of 0.0329 seconds, a rising time of 0.0208 seconds, and no overshoot. The simulation findings are encouraging and confirm the efficacy of the proposed technique. Ultimately, a statistical analysis is conducted to confirm the superiority of the proposed method.*

Key words: *Artificial Hummingbird Algorithm, DC Motor Control, Fractional Order PID*

1. INTRODUCTION

DC motor drives are commonly used in applications that need adjustable speed, precise speed regulation, and frequent starting, braking, and reversing [1]. Some notable uses of these systems include rolling mills, paper mills, excavators, and cranes [2]. Servo motors, commonly employed for the purpose of positioning, tracking, and actuating robotic arms [3] are generally DC motors with a power rating less than one horsepower. These applications often require a high degree of accuracy for position monitoring and motor speed regulation. In order to achieve these goals, control systems aim to optimise

Received July 20, 2024; revised September 5, 2024; accepted October 10, 2024
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the dynamic performance of the motor in order to carry out the designated task. PID controllers are commonly employed because to its simplicity, effectiveness, and robustness. Conversely, the FOPID controller is an improved version of the conventional PID controller that incorporates fractional derivative-integral calculus [4]. The FOPID controllers have two additional parameters of denoted as λ, and μ. The integration of supplementary functionalities into traditional PID controllers improves the system's robustness and flexibility [5]. The PID controller tuning is a complex procedure mostly achieved through either empirical experimentation or computational methodologies. The Ziegler-Nichols tuning method is commonly acknowledged as the most esteemed tuning approach that depends on empirical guidelines. However, such approaches are time consuming and come with risk of damaging the hardware used in the control process. Lately, researchers have proposed optimization-based techniques for control of DC motors in various applications. These approaches entail selecting error terms as the objective function.

In [6], the Grey Wolf Optimization (GWO) was utilized to tune PID and FOPID parameters employing the ITAE objective function. Subsequently, these controllers were assessed in comparison to Invasive Weed Optimization (IWO-PID) [7] and Stochastic Fractal Search (SFS-PID) [8] controllers. Their results indicated that the GWO tuned FOPID strategy, when using the ITAE performance criterion, achieves faster convergence and risetimes, while keeping similar levels of overshoot compared to other well-known strategies. A Particle Swarm Optimization (PSO-FOPID) controller is created and assessed in [9] using four different performance indices. Subsequently, the PSO-FOPID controller was compared with PSO tune PID controller. Their results indicate that the FOPID performed better, and the ITAE objective function produced the most favourable parameters compared to the other objective functions used. The paper [10] presents the development of a Constrained Particle Swarm Optimization (CPSO-FOPID) controller that integrates an ITSE objective function. This controller is characterised by five output constraints derived from observations of time and frequency response. The constraints include the time it takes for a system to settle, the percentage by which it exceeds its desired value, and the amount of phase shift allowed before instability occurs. Other algorithms that have been documented in the past decade include Artificial Bee Colony (ABC) [11], Jaya Optimization Algorithm (JOA) [12], and Flower Pollination Algorithm (FPA) [13]. The study cited in [14] focused on the development of Atom Search Optimization (ASO-PID), ASO-FOPID, and Chaotic Atom Search Optimization (ChASO-FOPID) controllers for the DC motor. The authors used ITAE and ITSE as the objective functions. The controllers were compared with GWO, IWO, and SFS tuned controllers. The results demonstrate that both ASO and ChASO based FOPID controllers performed better. The algorithm Henry Gas Solubility Optimization (HGSO) and its oppositional based version were used to tune the DC motor controller through ITAE objective function [15]. After a comparative assessment, it was concluded that the OBL/HGSO tuned PID controller is more robust and has better control performance as compared to SFS, ASO, and GWO algorithms. The Harris Hawk Optimization (HHO-PID) controller described in reference [16] was implemented to control the DC motor speed. This controller employs a mathematical model that mimics the trapping activity found in hawks. The goal was to minimise the ITAE value. The efficacy of the algorithm was evaluated by conducting a comparative analysis with previously published approaches, utilising assessments of transient responsiveness and resilience. The results demonstrated that the HHO-PID algorithm surpassed the other controllers in terms of its step response, displaying reduced peak overshoot, rising time, and settling time. Leader based Harris Hawk Optimization (LHHO), an altered form of HHO, [17], was developed with the specific aim of addressing the PID tuning issue. It does this by actively limiting the development of local optima and fostering variation within the hawk population inside HHO. The authors showcased the algorithm advantages by doing a comparison examination of the controller performance in relation to other published methodologies. Authors of [18] proposed a more advanced iteration of the ASO method. Incorporating the Simulated Annealing (SA) algorithm as a fundamental element significantly improved the search performance of ASO. The authors evaluated the performance by carrying out transient, frequency, and robustness evaluations and compared the findings with those of existing research. A PID controller was developed in [19], utilising a novel hybrid method that combines the Levy Flight Distribution (LFD) algorithm with the Nelder Mead (NM) algorithm, which is a simplex search methodology. Authors of [20] have implemented Slime Mould Algorithm (SMA) to tune the parameters of PID controller to control the speed of DC motor and regulate the terminal voltage of Automatic Voltage Regulator (AVR) system. In [21], Gazelle Optimization Algorithm (GOA) is combined with NM technique to form a hybrid algorithm and utilized to tune the PID controlled DC motor system. The authors reported superior time and frequency domain performance. The GOA is used to tune FOPID controller in [22], to control DC motor. The authors used ZLG as the objective function to be minimized and compared the obtained results with previous reported findings.

Many PID and FOPID controllers that rely on meta-heuristics, as documented in research, are sensitive to time-varying dynamics, significant parameter uncertainty, nonlinearity and premature convergence. These problems result in poor control performance, severe overshooting and sometimes instability. To tackle these issues, the authors have developed a method to evaluate the robustness and adaptability of the Artificial Hummingbird Algorithm (AHA). The motivation behind selection of AHA is the algorithm's effectiveness in search space exploration ability to offset the effects of uncertainties and nonlinearities of the system. Some of the advantages of AHA are:

- AHAs integrate adaptive search and Levy flight, which improves their global search ability and search accuracy.
- AHAs have been shown to be competitive in terms of computational speed and robustness for parameter estimation in the recent published articles.
- As far as authors’ knowledge is concerned, there is currently no existing literature that suggests a study on the utilisation of AHA for enhancing the speed control of DC motors.
- The contributions of the proposed work can be summarized in the following points:
- The study introduces the use of Artificial Hummingbird Algorithm for tuning Fractional Order PID (FOPID) controllers, a novel approach not explored in existing literature, especially for the speed control of DC motors.
- The research emphasizes evaluating the robustness and adaptability of AHA in addressing time-varying dynamics, significant parameter uncertainty, and system nonlinearities, which are common challenges in control systems.
- The proposed method demonstrates superior performance in managing uncertainties and nonlinearities compared to traditional PID and FOPID controllers, which often struggle in such conditions.

- The study includes a thorough comparative analysis of the proposed AHA-based method against other algorithms, showcasing its effectiveness through transient response performance and load disturbance tests.
- The research incorporates statistical analyses to validate the distinctiveness and superiority of the proposed method, providing a robust foundation for its efficacy.

The rest of the paper is organised as follows: Section 2 elaborates the mathematical modelling of DC motor, PID controllers and FOPID controllers. Section 3 provides a concise summary of the AHA algorithm, and the use of the AHA method to tune the FOPID controller. Section 4 explores the numerical results obtained from the proposed AHA-FOPID controller. Ultimately, concluding remarks are succinctly presented in Section 5.

2. Modelling of System Components

The focus of this research is on analysing a control system that consists of a controller and a DC motor, which serves as the plant. Speed control of the DC motor is the prime objective of this system. This section provides details of system components and their mathematical models.

2.1. DC Motor Modelling

This study examines the use armature voltage control method to adjust the speed of DC motor (externally excited). Fig.1 illustrates the electrical circuit of the field and armature winding, as well as the forces applied to the rotor [23]. The abbreviations for the parameters are listed in the symbol list.

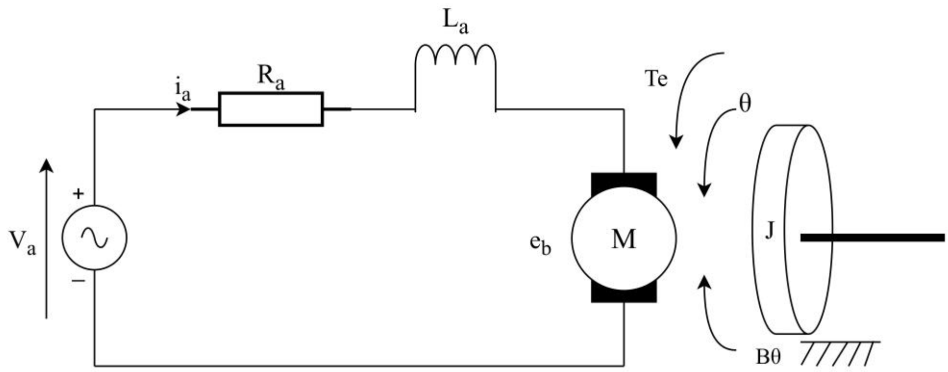

Fig. 1 DC Motor Circuit

DC motor speed control is commonly performed by adjusting the armature voltage (V), when a current (i) passes through the motor, an electromechanical force is produced in accordance to the angular speed. Applying Kirchhoff's voltage law to armature circuit of Fig. 1.

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + e_b \tag{1}$$

Assuming the field flux to be constant, the induced back emf e_b in the motor and the velocity $\omega = d\theta/dt$ are directly proportional.

$$e_b = K_b \frac{d\theta}{dt} = K_b \omega \tag{2}$$

The torque developed in the motor is:

$$T_e = J \frac{d\omega}{dt} + B\omega = Ki_a \tag{3}$$

Equation (3) excludes the load torque as it is seen as a disruptive element in the DC motor control system. The equations (1-3) can be converted into the s-domain using Laplace transform by assuming initial conditions of the system zero:

$$V_a(s) = (L_a s + R_a) I_a(s) + E_b(s) \tag{4}$$

$$E_b(s) = K_b \omega(s) \tag{5}$$

$$T_e(s) = (Js + B)\omega(s) = KI_a(s) \tag{6}$$

Block diagram representation of a DC motor system is shown in Fig. 2.

The transfer function of a DC motor, which quantifies the correlation between the output motor speed in terms of input voltage, may be represented as:

$$G(s) = \frac{\omega(s)}{E_a(s)} = \frac{K}{(L_a s + R_a)(Js + B) + K_b K} \tag{7}$$

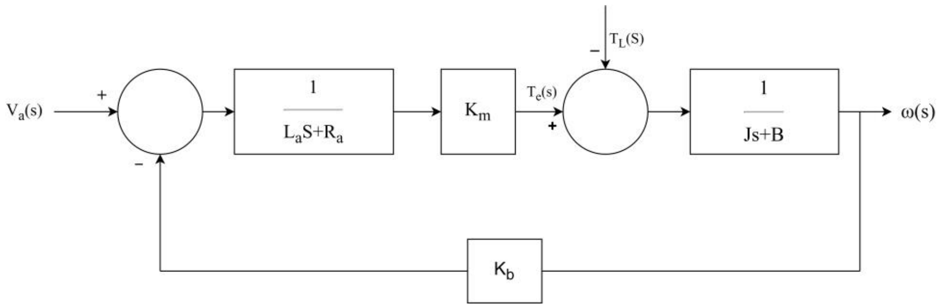

Fig. 2 Block diagram of DC motor

2.2. PID Controlled DC Motor

PID control employs a negative feedback closed-loop control approach to ensure that the actual output closely matches the intended setpoint. Equations (8) and (9) delineate the PID controller’s mathematical representation and transfer function.

$$u(t) = K_p e(t) + K_i \int e(t) + K_d \frac{d}{dt} e(t) \tag{8}$$

$$G_{PID} = K_p + \frac{K_i}{s} + K_d s = K_P + K_i s^{-1} + K_d s \tag{9}$$

Fig 3 represents the PID-controlled DC Motor employing unity feedback, and can be represented mathematically using Eq. (10).

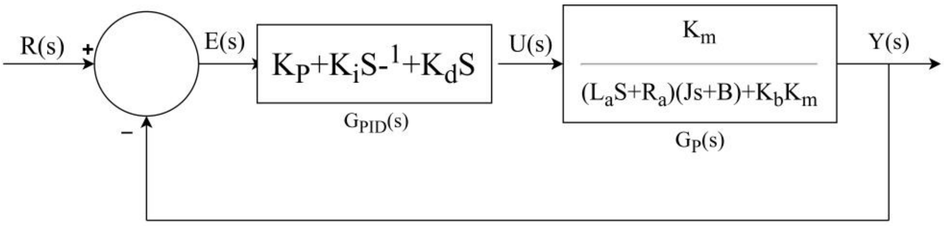

Fig. 3 PID controlled DC motor

$$G_{DC-PID} = \frac{K(K_p + K_i s^{-1} + K_d s)}{(L_a s + R_a)(Js + B) + K_b K + K(K_P + K_i s^{-1} + K_d \ s)} \tag{10}$$

2.3. FOPID Controlled DC Motor

FOPID controllers differ from integer order PID controllers by having two additional tuning parameters, namely λ and μ. Equation (11) presents the mathematical expression of a FOPID controller, whereas equation (12) represents its transfer function.

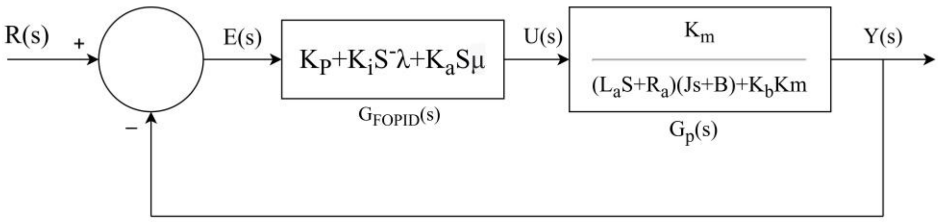

Fig. 4 FOPID controlled DC motor

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \tag{11}$$

$$G_{FOPID} = K_p + K_i s^{-\lambda} + K_d s^{\mu} \tag{12}$$

The closed loop transfer function of FOPID controlled DC motor can be expressed using Eq. (13)

$$G_{DC-FOPID} = \frac{K(K_P s^{\lambda} + K_i + K_d s^{\lambda} + \mu)}{\left[(L_a s + R_a)(Js + B) + K_b K\right] s^{\lambda} + K(K_p s^{\lambda} + K_i + K_d s^{\lambda} + \mu)} \tag{13}$$

2.4. Objective Functions

The objective function is a crucial measure utilised to optimise the design parameters for PID/FOPID controllers, guaranteeing the best possible performance. The purpose of this is to get precise control objectives. The objectives may encompass the reduction of overshoot, the decrease of settling time, the minimization of steady-state inaccuracy, and the attainment of stability. The primary goal of the system is to minimize the error input to the controller which is a difference between the actual and intended output of the system, this error is used as a measure to quantify the effectiveness of the controller. Prior studies have utilised several objective functions to effectively control the speed of DC motors to a pre-established target value. Equations (14-17) specify the often employed objective functions for tuning the DC motor controllers.

$$IAE = \int_0^{t_{sim}} |e(t)| dt \tag{14}$$

$$ISE = \int_0^{t_{sim}} e^2(t) dt \tag{15}$$

$$ITAE = \int_0^{t_{sim}} t|e(t)| dt \tag{16}$$

$$ITSE = \int_0^{t_{sim}} te^2(t) dt \tag{17}$$

3. ARTIFICIAL HUMMINGBIRD ALGORITHM

3.1. Origin of the algorithm

Zhao and Mirjalili developed the Artificial Hummingbird Algorithm (AHA) [24] a metaheuristic technique that relies on a population-based approach. The bio-inspired algorithm emulates the foraging and specialised flying methods of hummingbirds in order to discover viable solutions. Hummingbirds have three distinct foraging strategies: guided, territorial, and migration. While foraging, they display axial, diagonal, and omnidirectional flying patterns. Within the algorithm, the food source serves as a representation of the solution vector. Every hummingbird is allocated to a certain food source. The solution's quality is assessed based on the pace at which nectar is replenished in a food source. The algorithm stores the precise coordinates of the food supply and the pace at which nectar is replenished, and subsequently disseminates this information to other members of the group. This exchange of knowledge enables the AHA to swiftly and effectively arrive at feasible solutions. Hummingbirds utilise the concept of the visit table to navigate towards food sources that have a high frequency of visiting. This is due to the fact that food sources that are often visited tend to have higher rates of nectar filling, which in turn correspond to more optimal solutions. The subsequent sub-sections elucidate the fundamental principles of the AHA.

3.1.1. Initialization

AHA begins by producing potential solutions that are randomly dispersed. Upon arrival in a new region, each artificial hummingbird in the colony will engage in random exploration of food sources as part of the initialization process. Hummingbirds accidentally investigate primary sources of food. The i^{th} solution vector is initialized using Eq. 18.

$$x^i = rand.(ub - lb) + lb; i = 1,....., n \tag{18}$$

where, *rand* is a random number between 0 and 1, *lb* and *ub* represent upper and lower boundary of the solution vector.

The visit table is initialized by Eq. 19.

$$VT_{i,j} = \begin{cases} 0 \\ null \end{cases} if_{i=j}^{i \neq j} \tag{19}$$

where, the term "null" indicates that hummingbirds rely on a consistent food supply, whereas a value of "0" indicates that the i^{th} hummingbird has explored the j^{th} food source.

3.1.2. Guided Foraging

This strategy involves each individual hummingbird selecting its specific food source. The target source is determined based on two factors: the rate at which the nectar is refilled and the level of visits to the source. The hummingbird's flight designs can be adapted to navigate in multi-dimensional spaces. The hummingbirds travelling along the axis to reach any location is known as axial flight and is defined by Eq. (20).

$$D_{Af}^{(i)} = \begin{cases} 1 \\ 0 \end{cases} if_{else}^{i = randi([1,d])} \tag{20}$$

The diagonal flight is given by Eq. (21).

$$D_{Df}^{(i)} = \begin{cases} 1 \\ 0 \end{cases} if_{else}^{i=P(j); j \in [1,k]; P = randperm(k); k \in \left[2, \lceil r_1.(d-2) \rceil + 1\right]} \tag{21}$$

Eq. (22) expresses the omnidirectional flight.

$$D_{Of}^{(i)} = 1; i = 1,..., d \tag{22}$$

Equation (23) denotes the update factor, which is employed to modify potential solutions via guided foraging.

$$v_i(t+1) = x_{i,tar}(t) + a \cdot D \cdot (x_i(t) - x_{i,tar}(t)) \tag{23}$$

$$a \approx N(0,1) \tag{24}$$

where, $x_{i,tar}(t)$ is the target solution's position.

The equation below represents the update formula used by the hummingbird when it finds a place that is closer to the target supply of food.

$$x_i(t+1) = \begin{cases} x_i(t) \\ v_i(t+1) \end{cases} if_{else}^{f(x_{i(t)}) \leq f(v_{i(t+1)})} \tag{25}$$

3.1.3. Territorial Foraging

The hummingbirds update candidate solutions by territorial foraging using update equation (Eq. 26)

$$v_i(t+1) = x_i(t) + b \cdot D \cdot x_i(t) \tag{26}$$

$$b \approx N(0,1) \tag{27}$$

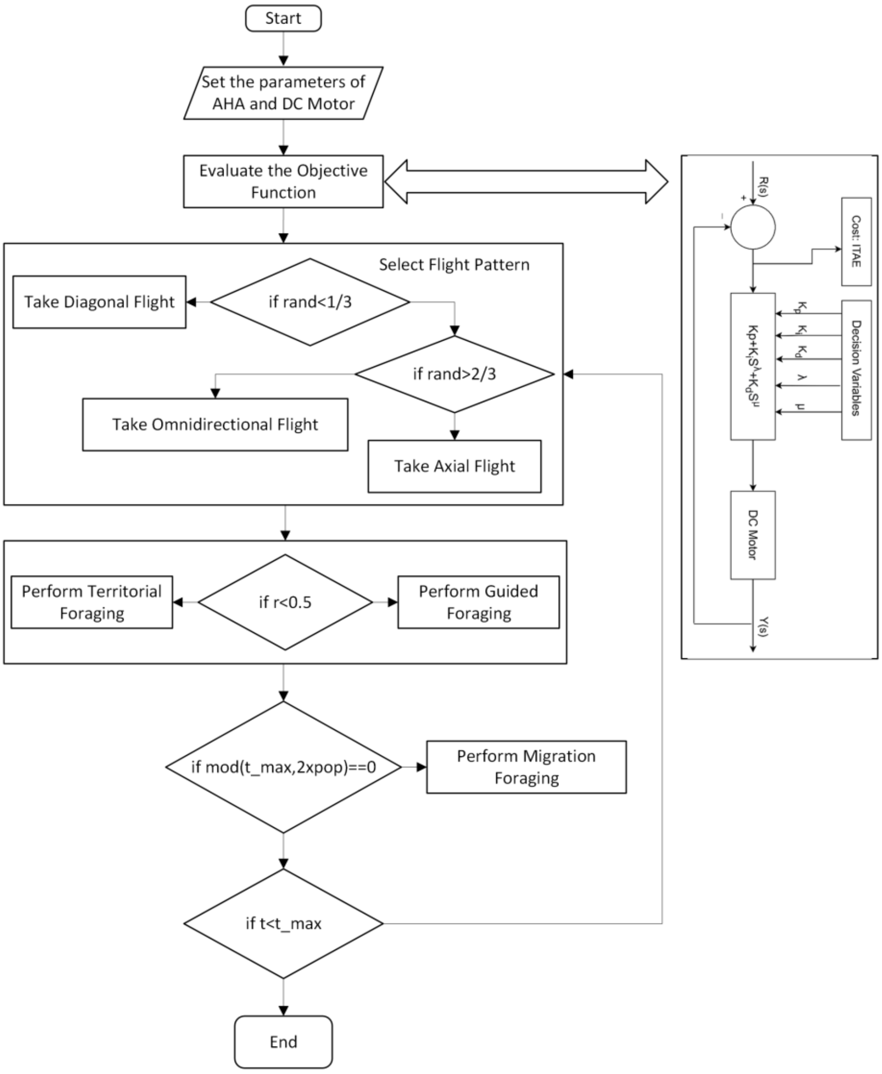

Fig. 5 Flowchart of proposed AHA-FOPID approach

Where, D represents one of the flight modes and b is territorial factor.

3.1.4 Migration Foraging

The equation for the movement of hummingbirds with worst position to find a better source of food via migration foraging is as follows:

$$x_{worst}(t+1) = r \cdot (ub - lb) + lb \tag{28}$$

Where, x_{worst} represents the candidate solution with worst position.

3.2. Artificial Hummingbird Algorithm for DC Motor Control

The flowchart of the AHA applied to tune the FOPID controller for DC motor speed control is shown in Fig. 5.

4. RESULT AND DISCUSSION

The simulated case studies, aimed at showcasing the efficacy of the proposed AHA-FOPID for regulating the speed of a DC motor, are carried out using MATLAB R2023b software on a PC equipped with an Intel Core-i5 CPU operating at a frequency of 2.0 GHz and 16 GB of RAM. The FOMCON toolbox has been utilised for fractional order modelling. Table 1 contains the specifications of the AHA and DC motor. The performance evaluation of the suggested technique started by minimising the ITAE value. The system's time domain response was assessed for a step input, followed by load disturbance test. The efficiency of the proposed strategy has been demonstrated via the statistical analysis of the obtained results.

Table 1 Parameters of the algorithm and DC motor

Parameter	Value
No of Hummingbirds	50
Lower bound	[20 20 20 2 2]
Upper bound	[0.001 0.001 0.001 0 0]
No of iterations	30
Simulation time	1 sec
L_a	2.7 H
R_a	0.4 Ω
B	0.0022 N-m-s/rad
J	0.0004 kg-m^2
K	0.015 N-m/A
K_b	0.05 V-s

4.1. Convergence Curve

The AHA-FOPID algorithm, which is being proposed, utilises the ITAE value as its objective function for optimising the controller gains of the DC motor. The optimal gain parameters derived from various techniques following a successful optimization action are presented in Table 2. Table 3 presents a comparison of the optimal objective values achieved by AHA-FOPID, as well as many reformed algorithms (GWO, PSO, and DE), and previously published results. The suggested AHA-FOPID approach has the lowest ITAE value compared to all the other methods being investigated. Figure 6 displays the convergence curve for minimizing the ITAE value by the considered techniques. It is evident that the algorithm exhibits a high rate of convergence.

Table 2 Optimal parameters of the proposed and studied controllers

Algorithm	K_p	K_i	K_d	λ	μ
AHA-FOPID	20	20	7.8011	0.3494	0.9209
AHA-PID	19.2511	5.1214	3.2240	-	-
GWO-PID	19.5690	5.7786	3.2936	-	-
PSO-PID	11.1989	3	1.8759	-	-
DE-PID	18.7927	3	3	-	-

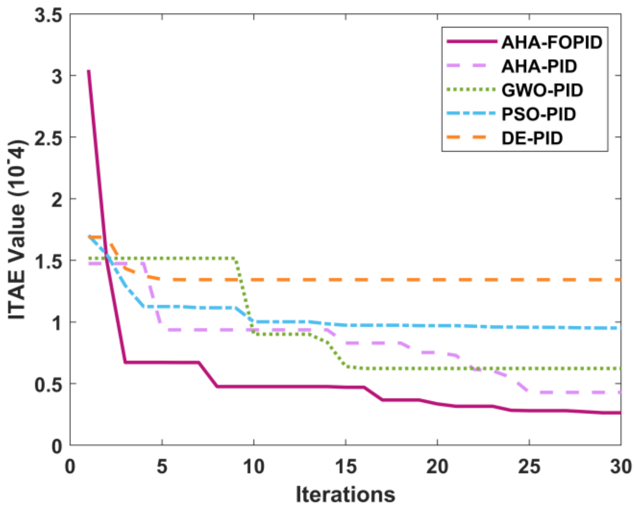

Fig. 6 Convergence profile of different algorithms for ITAE value as objective function

Table 3 Comparison of lowest achieved ITAE objective function value

Algorithm	Reference	ITAE
ASO-PID	[14]	0.003397
HGSO-PID	[15]	0.003047
HHO-PID	[16]	0.001042
PSO-PID	[9]	0.002496
DE-PID	Studied	0.0009567
PSO-PID	Studied	0.0009511
GWO-PID	Studied	0.0006207
AHA-PID	Studied	0.0004288
AHA-FOPID	**Proposed**	**0.0002406**

4.2. Step Response of DC Motor

To assess the transient performance of the suggested controller, the authors simulate the closed-loop DC motor system with the controller gains listed in Table 2. Settling times are determined based on a ±2% error range, and the time it takes for the motor to go from 10% to 90% speed is treated as the rising time. The transient response values are listed in Table 4. Fig. 7–12 display the comparative step responses. Based on the examination of the step response, it is evident that the suggested AHA-FOPID has superior transient performance, characterized by a settling time of 0.0329 seconds, a rising time of 0.02 seconds, and no overshoot.

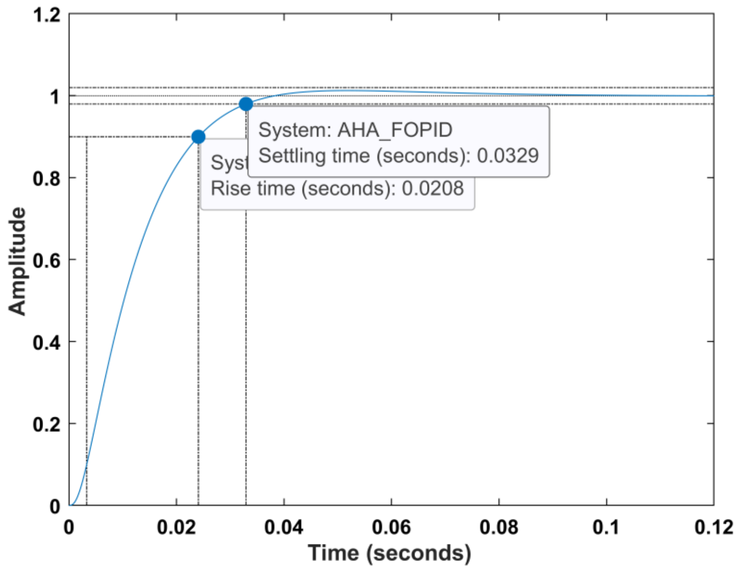

Fig. 7 Step response of AHA-FOPID controlled DC motor

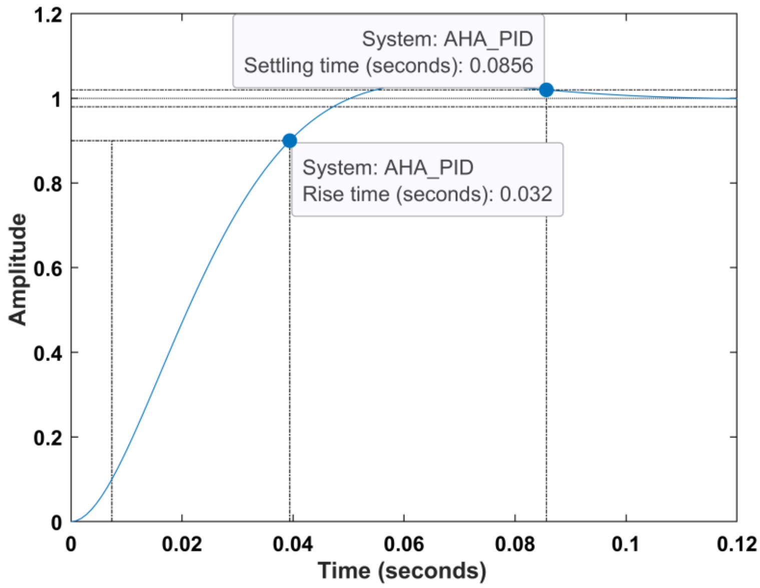

Fig. 8 Step response of AHA-PID controlled DC motor

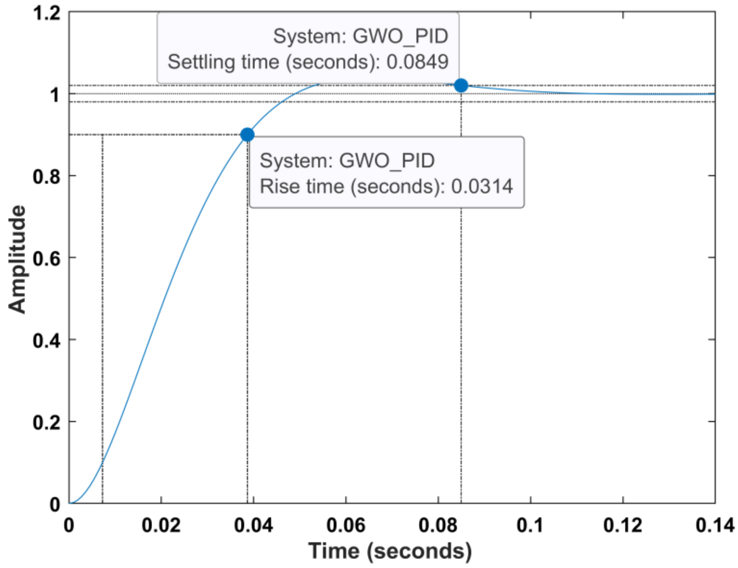

Fig. 9 Step response of GWO-PID controlled DC motor

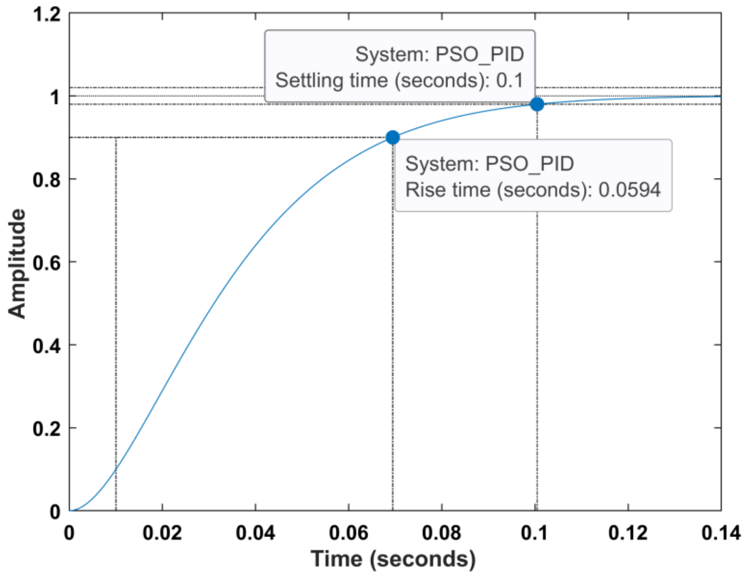

Fig. 10 Step response of PSO-PID controlled DC motor

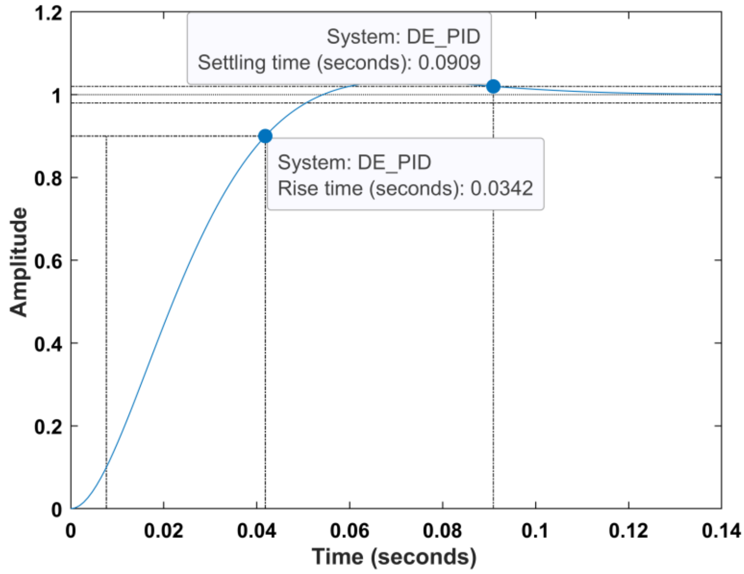

Fig. 11 Step response of DE-PID controlled DC motor

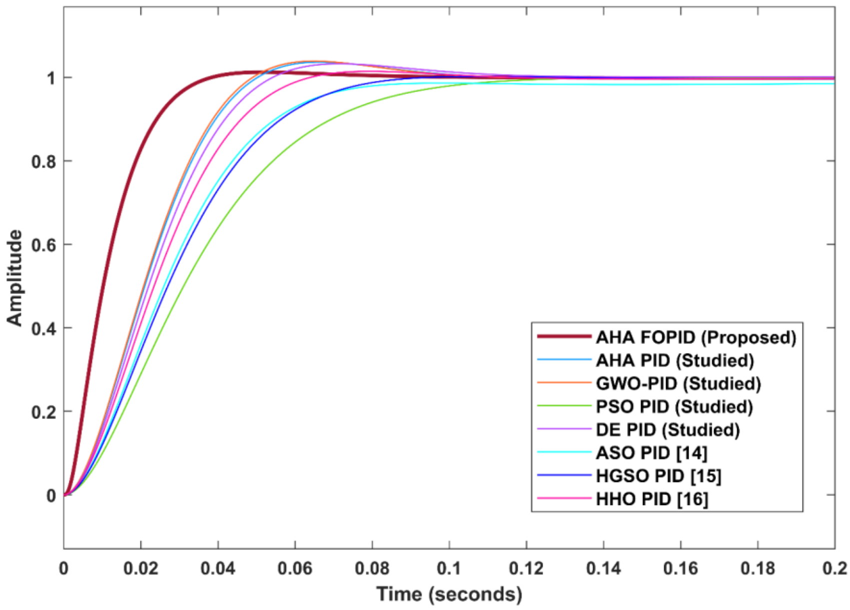

Fig. 12 Combined Step response of different controllers

Table 4 Comparison of transient response performance

Controller	References	Settling Time (s) (±2%)	Rise Time (s) (10-90 %)	Overshoot (%)
ASO-PID	[14]	0.1535	0.0692	0
HGSO-PID	[15]	0.06	0.07	0
HHO-PID	[16]	0.1003	0.0568	0
PSO-PID	[9]	2.38	0.409	25.5
GWO-FOPID	[25]	0.1172	0.058	0.51
ASO-FOPID	[14]	0.0616	0.0376	0
DE-PID	Studied	0.0342	0.909	3.24
PSO-PID	Studied	0.1	0.0594	0
GWO-PID	Studied	0.0849	0.0314	3.87
AHA-PID	Studied	0.0856	0.032	3.64
AHA-FOPID	Proposed	**0.0329**	**0.0208**	**0**

4.3. Response of DC Motor for Ramp Input

To assess the performance of the DC motor for a ramp input, a ramp signal that rose from 0 to 1 linearly in 0.1 second is applied as the input for the considered system. The comparative performance of the proposed and other studied controllers is plotted in Fig. 13. It can be seen that the proposed AHA-FOPID controller has outperformed other controllers by settling to the final steady state value within 0.11 second without any overshoot.

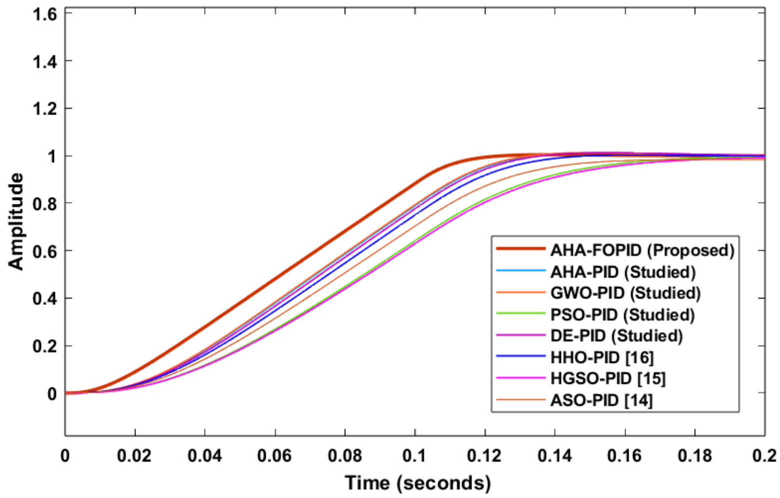

Fig. 13 Response of different controllers for ramp input

4.4 Frequency Response Analysis

Frequency response analysis is performed to validate the stability of a feedback system. Bode diagram of the proposed AHA-FOPID controlled DC motor system is shown in Fig. 14 and the frequency response parameters are tabulated in Table 5. It can be seen that the gain margin and phase margin offered by the proposed controller are infinite and 180 degrees respectively.

Table 5 Frequency response performance of controllers

Algorithm	Phase Margin (deg)	Gain Margin (dB)
ASO-PID [14]	180	Infinite
HGSO-PID [15]	180	Infinite
HHO-PID [16]	178.9	Infinite
DE-PID	165	Infinite
PSO-PID	180	Infinite
GWO-PID	180	Infinite
AHA-PID	180	Infinite
AHA-FOPID	**180**	**Infinite**

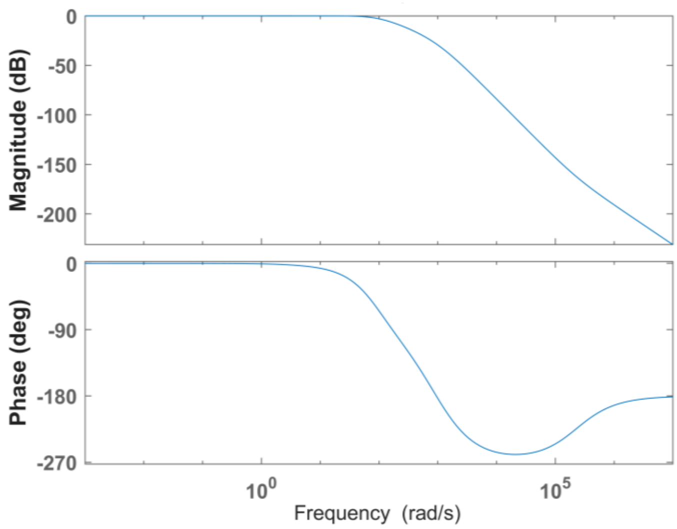

Fig. 14 Bode diagram of the proposed controller

4.5 Robustness Analysis

Since every system undergoes certain unpredictable changes whether it may be the parametric changes or environmental condition changes. Nonetheless, the controller must be robust enough to suppress any variation in the output due to such changes in system states. In order to validate the robustness of the proposed system, the authors have considered 4 different cases as tabulated in Table 6 by varying the values of armature resistance and motor torque constant in steps of ±25%.

Table 6 Parameter variations for robustness analysis

Case	Ra (Ω)	K (N-m/A)
1	0.3	0.012
2	0.3	0.018
3	0.5	0.012
4	0.5	0.018

The performance of the proposed and studied controllers has been plotted in Fig. 15-18. The time domain specifications of the step response for considered cases are tabulated in Table 7. The results clearly demonstrate that the proposed AHA-FOPID controller consistently exhibits the lowest settling time and rise time values, without any overshoot, in all scenarios, as compared to all other controllers.

Table 7 Comparison of transient response performance for different cases

Controller	References	Settling Time (s) (±2%)	Rise Time (s) (10-90 %)	Overshoot (%)
		Case 1		
ASO-PID	[14]	0.1535	0.0692	0
HGSO-PID	[15]	0.06	0.07	0
HHO-PID	[16]	0.1003	0.0568	0
PSO-PID	[9]	2.38	0.409	25.5
DE-PID	Studied	0.0342	0.909	3.24
PSO-PID	Studied	0.1	0.0594	0
GWO-PID	Studied	0.0849	0.0314	3.87
AHA-PID	Studied	0.0856	0.032	3.64
AHA-FOPID	Proposed	**0.0329**	**0.0208**	**0**
		Case 2		
ASO-PID	[14]	0.1535	0.0692	0
HGSO-PID	[15]	0.06	0.07	0
HHO-PID	[16]	0.1003	0.0568	0
PSO-PID	[9]	2.38	0.409	25.5
DE-PID	Studied	0.0342	0.909	3.24
PSO-PID	Studied	0.1	0.0594	0
GWO-PID	Studied	0.0849	0.0314	3.87
AHA-PID	Studied	0.0856	0.032	3.64
AHA-FOPID	Proposed	**0.0329**	**0.0208**	**0**
		Case 3		
ASO-PID	[14]	0.1535	0.0692	0
HGSO-PID	[15]	0.06	0.07	0
HHO-PID	[16]	0.1003	0.0568	0
PSO-PID	[9]	2.38	0.409	25.5
DE-PID	Studied	0.0342	0.909	3.24
PSO-PID	Studied	0.1	0.0594	0
GWO-PID	Studied	0.0849	0.0314	3.87
AHA-PID	Studied	0.0856	0.032	3.64
AHA-FOPID	Proposed	**0.0329**	**0.0208**	**0**
		Case 4		
ASO-PID	[14]	0.1535	0.0692	0
HGSO-PID	[15]	0.06	0.07	0
HHO-PID	[16]	0.1003	0.0568	0
PSO-PID	[9]	2.38	0.409	25.5
DE-PID	Studied	0.0342	0.909	3.24
PSO-PID	Studied	0.1	0.0594	0
GWO-PID	Studied	0.0849	0.0314	3.87
AHA-PID	Studied	0.0856	0.032	3.64
AHA-FOPID	Proposed	**0.0329**	**0.0208**	**0**

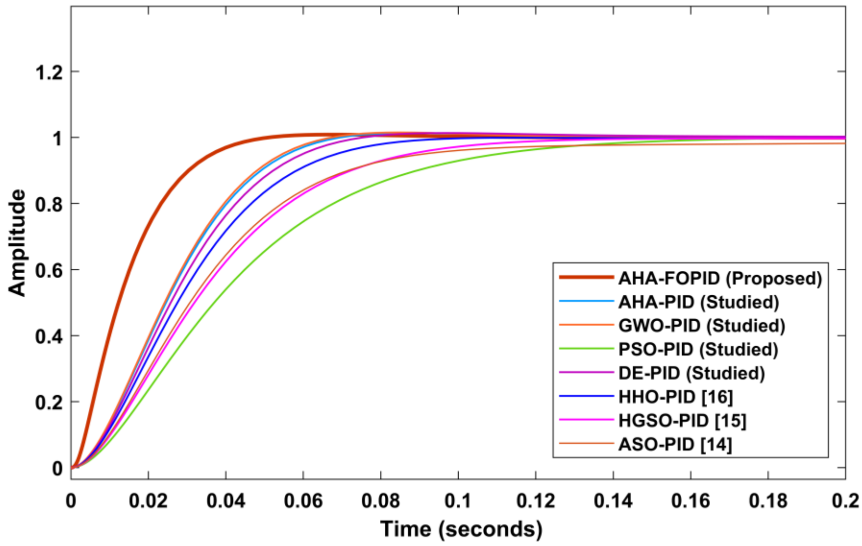

Fig. 15 Comparative step response for case 1

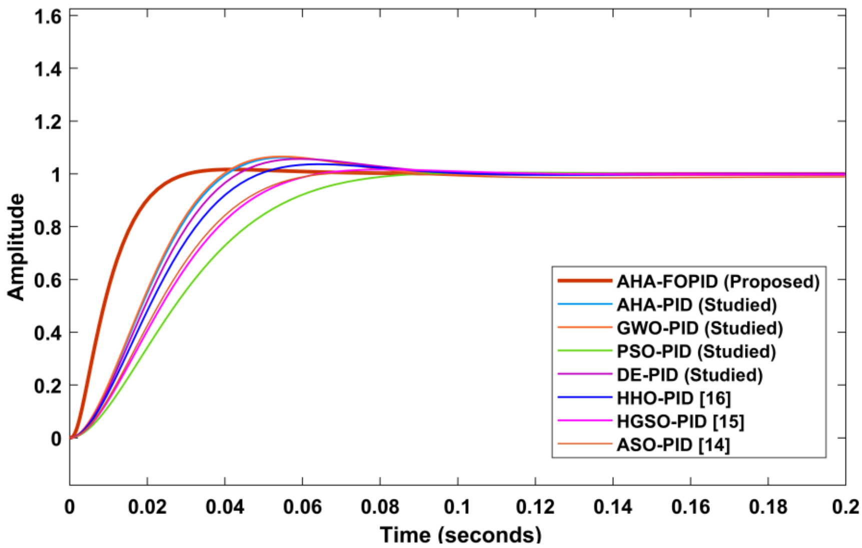

Fig. 16 Comparative step response for case 2

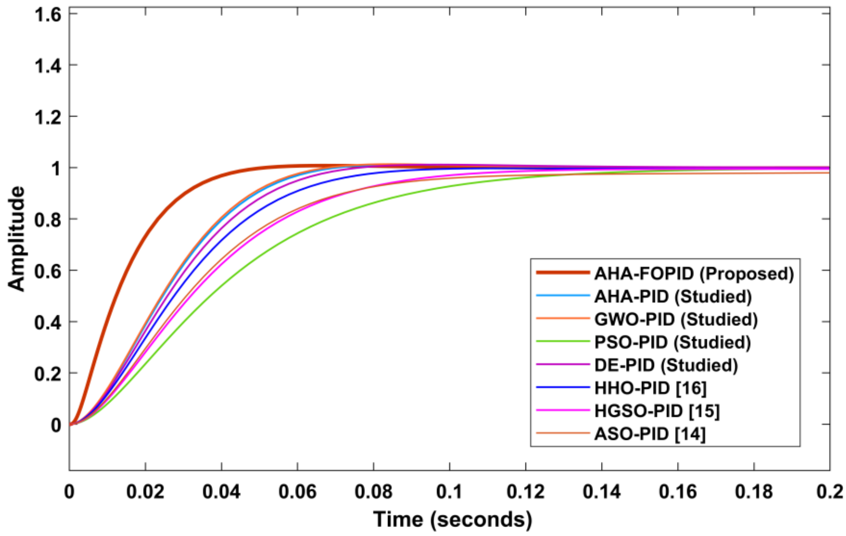

Fig. 17 Comparative step response for case 3

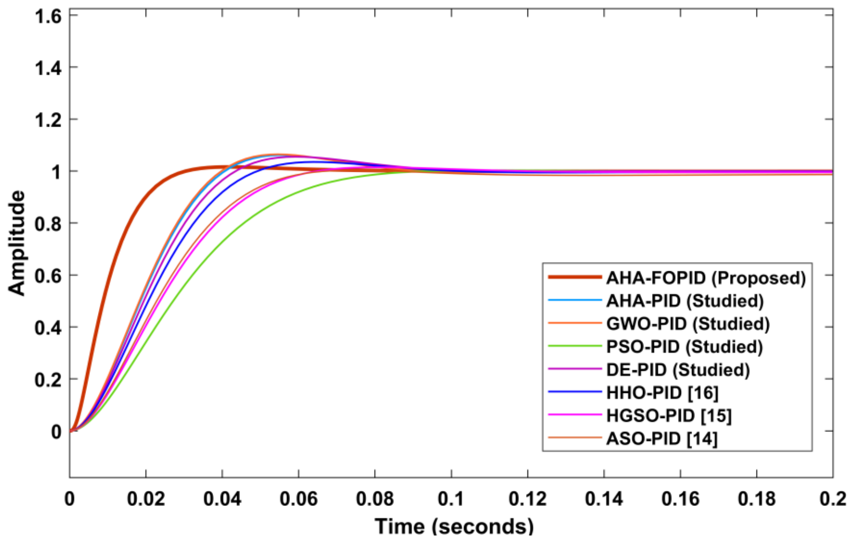

Fig. 18 Comparative step response for case 4

4.5. Load Disturbance Performance

The load disturbance test demonstrates the proficiency of the DC motor equipped with the suggested controllers, in efficiently handling various loads. Additionally, it includes an evaluation of alternative controllers that were specifically examined in relation to a step load disturbance. In the DC motor speed control system, it is crucial for the output speed response to quickly stabilize at zero when there is a change in load torque, in order to offset this disturbance. Fig. 19 depicts the dynamic reaction of the speed control system of a DC motor when it encounters a sudden change in load. The figure conclusively illustrates the superior performance of the AHA-FOPID controller compared to the other controllers in terms of its response to load disturbances, characterized by little undershoot and rapid settling time. Therefore, the suggested controller is extremely efficient in effectively mitigating the influence of load disturbances.

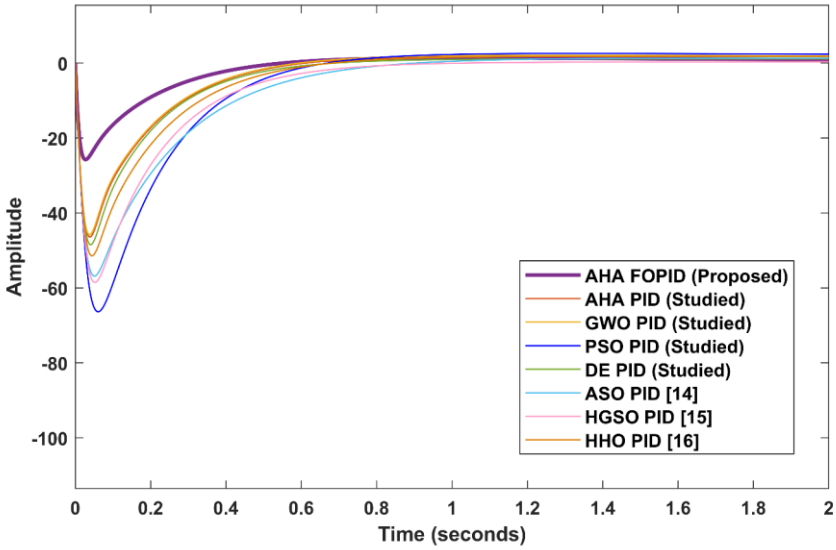

Fig. 19 Performance of DC motor with different controllers for step load disturbance

4.6. Statistical Analysis

The efficacy and efficiency of the suggested AHA-FOPID were evaluated by independently executing all algorithms under investigation 30 times to tune the controllers of the studied DC motor system. Figure 20 displays a box plot that represents the performance of several algorithms. A box plot graphically displays the interval between the lowest and highest data values, using lines that extend from the box. Table 8 displays numerical results obtained from the statistical analysis. AHA-FOPID demonstrates a greater likelihood of attaining lowest fitness function values, as indicated by the close closeness of its median to the bottom quartile.

Table 8 Statistical analysis of considered approaches for ITAE objective function

Controller	Best Value	Worst Value	Average Value	Standard Deviation
AHA-FOPID	**0.000241**	**0.000321**	**0.000253**	**1.69699E-05**
AHA-PID	0.000429	0.000559	0.000479	3.75452E-05
GWO-PID	0.000621	0.000985	0.000799	0.0001289
PSO-PID	0.000951	0.001343	0.001017	0.0001456
DE-PID	0.000956	0.001339	0.001114	0.0001211

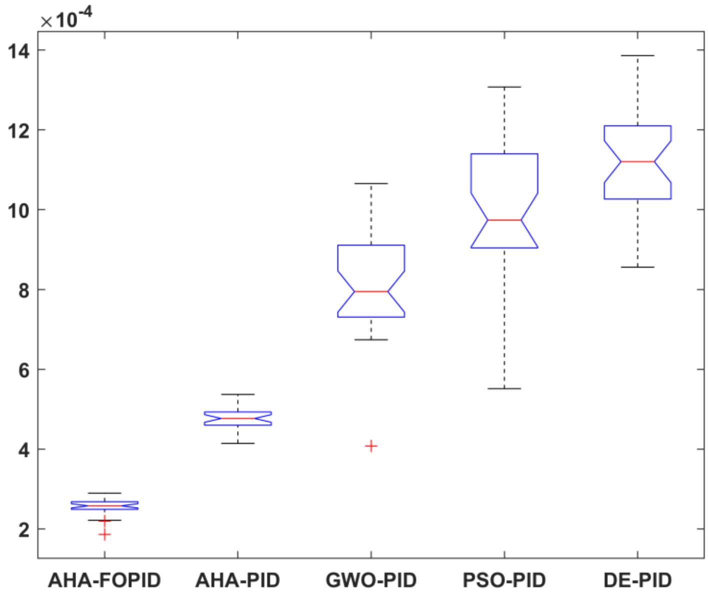

Fig. 20 Box Plot of ITAE objective function values

5. Conclusion and Future Scope

Optimising the FOPID controller parameters is an exceedingly complex task. If the controller does not get tuned properly, the control system becomes inefficient and the control performances gets deteriorated. This paper proposes the application of an AHA-FOPID controller, which is based on the AHA algorithm inspired by the foraging techniques of hummingbirds, as a novel strategy for controlling the speed of DC motors. The AHA algorithm was employed to minimise the ITAE objective function in a DC motor speed control system with a FOPID controller with unity feedback. The suggested approach took fewest no of iterations to converge towards the optimal FOPID parameters. To showcase the efficiency of the proposed AHA-FOPID method, authors conducted performance comparisons with some reformulated techniques and previously published results. The comparison revealed that the suggested AHA-FOPID controller had superior transient and frequency response characteristics, and was more effective in mitigating sudden changes in the system output caused by load disturbances. Ultimately, the statistical analysis provided conclusive evidence of the superiority of the proposed strategy. However, AHA does present some limitations such as facing a challenge in achieving a balance between exploration and exploitation, which may lead to stagnation in local optima, and the effectiveness of AHA heavily relies on the careful selection of objective functions, nectar filling rate, and population size, which may require extensive tuning.

In the future, the proposed work could be validated by testing it against non-metaheuristic algorithms and conducting real-world experiments. This would further strengthen the credibility of the proposed method and demonstrate its practical applicability.

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