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Control of the BLDC Motor Using Ant Colony Optimization Algorithm for Tuning PID Parameters

Yam Krishna Poudel[1],* and Pratap Bhandari[1]

[1]*Department of Electrical and Electronics Engineering, Nepal Engineering College, Nepal*

Abstract A key component of industrial applications is the direct current (DC) motor. Hence, due to their superior features and performance, brushless DC (BLDC) motors are more suitable for fractional kilowatt motor's applications. Albeit, for the purpose of controlling the speed of BLDC motor easily, it is quite difficult for obtaining the best controlling performance through the use of the conventional approaches of tuning. In order to search the proportional–integral–derivative (PID) tuning parameters optimally for the different controllers taken into consideration, the use of modern bio-inspired metaheuristic technique called ant colony optimization (ACO) algorithm is employed. This paper particularly discusses and presents on the tuning parameters of $k_p,\ k_i,\ and\ k_d$. The performance of traditional controller and novel approach is compared, analyzed, and presented. BLDC motor is buildup in MATLAB, and the usage, importance, efficiency, and strength of the proposed approach are validated against traditional tuning methods. The obtained result shows better performance of the proposed system with the aid of the proposed controllers for different speed trajectories of the drive when compared with that of the classical PID controllers. ACO seems to be one of the most effective tuning techniques of PID controllers. This research has significant impact on modern control applications.

Keywords: brushless DC motor (BLDCM), ant colony optimization (ACO) algorithm, speed control, particle swarm optimization (PSO)

1. Introduction

Brushless direct current (BLDC) motors must have a motor body, position sensors, and an electronic commutation circuit (Shen, 1996). Electronic closed-loop controllers are used to switch DC currents toward the motor windings in BLDC motors (also known as electronically commutated motors). This contributes to or helps generate magnetic fields that rotate in space, following the rotor of a permanent magnet. BLDC motors can be used in place of conventional DC motors. They are a particular class of synchronous permanent magnet motors. BLDC motors are driven by DC voltage, and current commutation is aided by solid state switches. Rotor position explains the commutation instants that are picked up by position sensors or by methods without sensors quite well. The key objective of prospective and current applications is to reduce production costs while maintaining good performance (Vikhe et al., 2019).

Modern control strategies for speed control of BLDC motor include various systems of controls. One of those most commonly used control methods is non-linear control. Similarly, other various types and methods of control include optimal, variable structure, and adaptive control (Nasri et al., 2007). The controller modifies the phase and amplitude of the DC current pulses in order to control the motor's speed. Some designs use rotary encoders or Hall effect sensors to directly measure the position of the rotor. Other different sorts of designs, also known as sensor less controllers, monitor the back electromotive force (EMF) in the un-driven coils in order to find the location of the rotor in place of the independent requirement of a Hall effect sensor. Using a sensor less operation and adjusting applied voltage, a permanent magnet BLDC motor drive can also have its spinning speed controlled (Sivakami, 2019).

When compared to brushed DC motors, the benefits of BLDC motors outnumber and outweigh those of brushed DC motors, which is the primary reason for their expanding use in industries, appliance manufacturing, aerospace, medical, chemical, automotive, textile, automation, and other various fields (Li et al., 2004; Mishra & Narain, 2013; Wu & Tian, 2012). Brushless DC (BLDC) motors has better speed torque characteristics, where the motor torque can be evaluated, determined, and analyzed in order to from speed, high efficiency, long operating life, high dynamic response, higher speed range, reduction of arcing (Rubi Batham, 2017), noiseless operation, less requirement of repair, and maintenance as compared to the conventional systems.

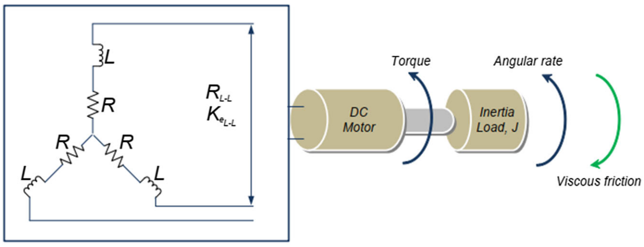
For the rotation of the motor, the windings of the stator are energized in order for the BLDC motor. Usually, linear BLDC motor is more efficient and has higher value of efficient with the requirement and need of less repair and maintenance (Sharma & Gupta, 2014). There is no physical contact between the stator and the rotor. Another essential component of BLDC motors is the Hall sensor, which is sequentially attached to the rotor. This serves as a primary sensing device for the stator's Hall effect

*Corresponding author: Yam Krishna Poudel, Department of Electrical and Electronics Engineering, Nepal Engineering College, Nepal. Email: yampdl01@gmail.com

sensor. The Hall effect is the foundation of the operation. The main mode of operation for BLDC motors is three phase, which has some cost implications but also offers good efficiency, good control precision, and low torque. However, it is necessary for the management of stator current.

The mathematical model of the BLDC motor resembles the ordinary DC motor in a variety of ways. In the mathematical formulation, the adding of the phases in BLDC motors differs from that in DC motors. These phases have an impact on the BLDC motor's resistive and inductive configuration. Figure 1 shows a simple arrangement with a symmetrical three-phase and star connected internal connection (Shrivastava et al., 2021).

Figure 1
Brushless DC motor schematic diagram



The construction of BLDC motors results in the induction of trapezoidal voltage in the armature's winding. In BLDC motors, where the stator has a trapezoidal waveform, the stator winding is concentrated. Following are the voltage equations, where e and P stand for the electromagnetic flux and the number of poles, respectively. The DC motor is coupled with the inertia load, J, and the DC motor rotates with desired torque. The motor drives the load at an angular rate with certain amount of viscous fiction. In Figure 1, the notations R_{l-l} represent the line-to-line resistance and K_{eL-L} represents the motor constants.

$$\mathrm{V_a = R_a i_{ph-a} + L_a p i_{ph-a} + L_{ab} p i_{ph-b} + L_{ac} p i_{ph-c} + e_{ph-a}} \quad (1)$$

$$V_b = R_b i_{ph-b} + L_b p i_{ph-b} + L_{ba} p i_{ph-a} + L_{bc} p i_{ph-c} + e_{ph-b} \quad (2)$$

$$V_c = R_c i_{ph-c} + L_c p i_{ph-c} + L_{ca} p i_{ph-a} + L_{cb} p i_{ph-b} + e_{ph-c} \quad (3)$$

The corresponding mathematical electromagnet torque is expressed in equation.

$$T = \frac{\left(e_{ph-a} i_{ph-a} + e_{ph-b} i_{ph-b} + e_{ph-c} i_{ph-c}\right)}{\omega} \quad (4)$$

$$e_{ph-a} = 0.5 K_e \omega F(\theta_e) \quad (5)$$

$$e_{ph-b} = 0.5 K_e \omega F\left(\theta_e - \frac{2\pi}{3}\right) \quad (6)$$

$$e_{ph-c} = 0.5 K_e \omega F\left(\theta_e - \frac{4\pi}{3}\right) \quad (7)$$

where k_e is the back EMF constant. $F(\theta_e)$ is a rotor position function that provides the trapezoidal waveform of the back EMF that is expressed in the equation shown below and θ_e is the electrical rotor angle.

$$F(\theta_e)\begin{cases} 1 & For\ 0 \le \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & For\ \frac{2\pi}{3} \le \theta_e < \pi \\ -1 & For\ \pi \le \theta_e < \frac{5\pi}{3} \\ 1 + \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & For\ \frac{5\pi}{3} \le \theta_e < 2\pi \end{cases} \quad (8)$$

For the purpose of achieving better performance of the controller, proper choice of tuning constants is one of the major concerns (Astrom & Hagglund, n.d.; Nagaraj et al., 2008).

2. Literature Review

Ridwan et al. (2017) implemented a BLDC motor speed controller based on particle swarm optimization (PSO) while taking response speed into account. The outcome demonstrates that a metaheuristic technique called PSO-based controller may be used to accurately manage the speed of BLDC motors with the anticipated reaction speed.

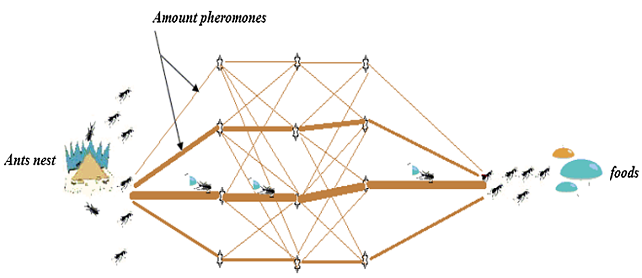
A high-precision servo control system based on fuzzy self-tuning proportional–integral–derivative (PID) is proposed to handle the rising motor vibration and torque ripple caused by the asymmetric air gap construction of single-phase BLDC motors. First, the mathematical model and state equations for the single-phase BLDC motor are derived. A fuzzy self-tuning PID simulation model is then created in order to simulate and produce a decent step response curve. The constructed physical platform is then used to compare and study the servo position accuracy of traditional PID and fuzzy self-tuning PID. Finally, the strategy is successfully applied to a fuel valve for a gas metering system (Jin et al., 2022).

Djalal and Faisal (2019) performed the research titled "Ant Colony based Proportional–Integral–Derivative (PID) Tuned Parameter for Controlling Synchronous Motor" that explains that optimal performance of the system can be achieved with minimum overshoot and quick settling, considering various scenarios of speed on a synchronous motor, as well as PID ant colony control.

Pant et al's. (2018) "Optimal Tuning of Proportional–Integral (PI) Speed Controller Using Nature Inspired Heuristics" shows how to compare and study various algorithms for the purpose of tuning proportional integral (PI) speed controllers in permanent magnet synchronous motor drives. The linear system is taken into account when tuning the PID controller, but the physical constraints, such as the maximum current and voltage, are not taken into consideration.

Shi et al's. (2022) PF-PI controller, which was reliant on the traditional and conventional form of BLDC control system, was

Figure 2
Illustration of bio-inspired algorithm ant colony optimization (ACO)



used or utilized in the proposed novice and innovative control system. Both the dynamic performance of the BLDC speed control system and the PI controller have been considerably improved.

Milani et al. (2012) determined ideal reduced rise time, settling time, and overshoot on system response using the proposed PID parameters BLDC motor PID – PSO – Ziegler–Nichols algorithm.

Bazi et al. (2021) presented a fast firefly algorithm (FA) algorithm and contrasted it with a standard FA through the use of various standard benchmark functions. The comparison of the simulation results was then performed while also taking the speed and accuracy of the criteria for comparing the algorithms into account.

Wang et al.'s (2022) dual fuzzy logic systems and harmony search algorithm (HAS) optimization were used to suggest a novice PID, which was given the name DFPID–HAS. Its superiority was demonstrated by simulation in MATLAB and experimental analysis utilizing the appropriate sort of platform.

In Shamseldin and EL-Samahy (2014), three unique resilient controller techniques for high performance BLDC motors are given. The rotor is made to follow a predetermined speed/position track in order to test the effectiveness of each control strategy. This objective ought to be achieved without the interference of changing parameters or outside disturbances. The first approach uses a standard PID controller. The second controller strategy uses a genetic algorithm to modify the PID controller settings (Shamseldin & EL-Samahy, 2014).

A particle swarm optimizer is used to control the PID gains of a BLDC motor (Portillo et al., 2009), which drives a milling machine. Three motors move along the coordinate axes, while one motor spins clockwise and counterclockwise.

BLDC motors are leading the present industrial trend toward the usage of extremely efficient and small permanent magnet motors for a variety of applications. Furthermore, the electric vehicle sector has identified BLDC motors as the most dependable and adaptable motors for changing industrial demands. The dynamics of a BLDC motor, on the other hand, are mostly determined by its driving performance. For decades, PI and PID controllers have been utilized for speed control of a BLDC motor, but they have the problem of needing to be tuned or retuned for every change in operating point to achieve optimal performance. Recent advancements in control systems have enabled auto-tuning of PID controllers to achieve maximum performance at varying operating speeds (Gadekar et al., 2020).

There are more than one ant working asynchronously or synchronously due to which the metaheuristic technique named ant colony optimization (ACO) is suitable for parallel working. Each ant works at the node at specific time. The ant leaves pheromone on traveling and used for prediction of ways of the other ants and hence gives common result. ACO algorithm is inspired by social behavior of real ants. ACO is basically inspired by pheromone-based ant communication.

For solving the PID controller design problem using ACO, three separate vectors include each of the parameter values (k_p, k_i, and k_d). These vectors may be routes between the nests for the purpose of representing the issue as a graph. By selecting the path between the starting and ending nodes, the ant should travel to three nests during the trip. ACO seeks to determine which of the three nests offers the best tour at the lowest possible cost. At the start of each path, the ants lay down pheromones.

In the proposed approach, the pheromones are updated by each of the ants that are deposited along the paths, which is followed after completion of one tour namely called local pheromone and hence can be updated as shown below. Illustration of bio-inspired algorithm ant colony optimization (ACO) in Figure 2.

$$\tau(k)_{ij} = \tau(k-1)_{ij} + \frac{0.01\theta}{J} \tag{9}$$

where $\tau(k)_{ij}$ is the value of the pheromone between the nests (i) and (j) at the k iteration, θ is the updating coefficient of general pheromone, and J is the cost function that accounts the tour that has been traveled by the ant.

Considering the global pheromone to update the rule, pheromones of the paths that belong to the best tour and the worst tour of the colony of the ant are modified and updated as shown below.

$$\tau(k)^{Best}{}_{ij} = \tau(k)^{Best}_{ij} + \frac{\theta}{J_{Best}} \tag{10}$$

$$\tau(k)^{Worst}{}_{ij} = \tau(k)^{Worst}_{ij} - \frac{0.3\theta}{J_{Best}} \tag{11}$$

where τ^{Best} and τ^{Worst} are pheromones along the paths that have been followed by the ant along the tour having the lowest cost value (J_{best}) and the highest cost value (J_{worst}) in one iteration, respectively.

In comparison to the routes belonging to the worst tour of the iteration, the paths that belong to the best tour of the colony exhibit much higher levels of pheromones. ACO focuses its search in new directions without getting stuck in any local minima.

$$(k)_{ij} = \tau(k)^{\lambda}{}_{ij} + \left[\tau(k)^{Best}{}_{ij} + \tau\Big(k\Big)^{Worst}{}_{ij}\right] \tag{12}$$

where λ is the evaporation constant.

3. Research Methodology

The fitness function for ACO is established with the aid of the reduction of error between the expected speed and the actual output speed of BLDC motor, and the corresponding error is calculated as:

$$e(t) = \omega_{reference} - \omega_{actual} \tag{13}$$

where $\omega_{reference}$ is the provided reference speed and ω_{actual} is the actual speed of the BLDC motor.

Integral time square error (ITSE) is used as the goal function in the cost function for ACO in order to achieve quick convergence. It is possible to write the fitness function as:

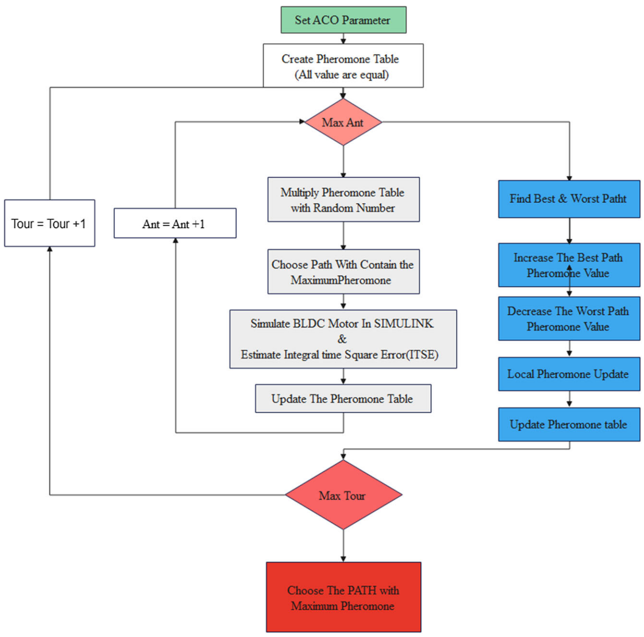
$$Integral\ time\ square\ error\ (ITSE) = \int_0^{\infty} t|e(t)|^2$$

$$Cost\ function = Minimization((ITSE)$$

For the purpose of optimizing the PID controller for ACO, first the ACO parameters are fixed and set as per the design and requirements for the purpose of analysis. After setting the parameters, the pheromone table is made and created in which all values are equal. Then, the loop surpasses into maximum ant loop. The pheromone table is then multiplied with the help of random number. The path is then finally chosen, which contains the maximum pheromone. The BLDC motor is simulated in SIMULINK and, the pheromone table is updated. The value of ant is again checked and if it is equal to one, then the loop continues. The best and worst path is selected, and the best path pheromone value is increased. Then, the worst path pheromone value is decreased. The local pheromone is then updated. Finally, the pheromone table is updated. Ultimately, at the end of the loop, the path with maximum pheromone is chosen.

Figure 3 clearly shows the PID optimization steps through the use of ACO. Fifty nodes were utilized in coding of PID controller in this section. One of the nodes represents the value of solution for the different parameters k_p, k_i, and k_d. More accuracy trails are updated as a result of the increased node count. At the conclusion of several tests, the ideal ACO parameters were found.

Figure 3
Algorithm for optimization of the PID controller of ACO

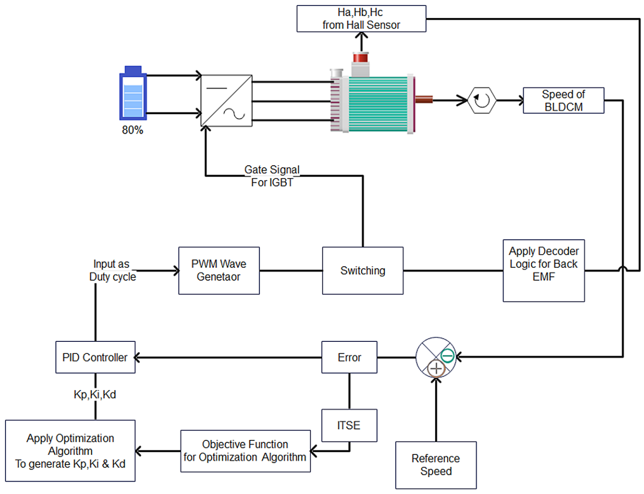


After the selection of the parameters of ACO, roads were provided with the equal number of pheromones. This leads to the concentration of all the artificial ants to this value decided and fixed at pheromone matrix. The ant selects random path as soon as the prior artificial ant leave through the nest, since the roads contain equal number of pheromones accessible to the ants. After the tour completion, simulation was carried out through the aid of the PID coefficients that have been selected. Thereafter, calculation of ITSE between reference speed and actual speed at the shaft of BLDC motor was calculated and roads value that passes through the artificial ant in the pheromone matrix was further modified and updated. Then, pheromone table was modified and updated by multiplying through a random number as next artificial ants were in different way in the road and did not approach in the same way. However, through the different coefficients of PID in each tour, the ants aim to track the reference route or the trajectory provided.

The amount of pheromone at the path of the artificial ant on the tour with the lowest ITSE is raised, whereas the amount at the path of the artificial ant on the tour with the greatest ITSE is lower than that of the beneficial ant. Additionally, the evaporation constant (λ) is used to evaporate the pheromone concentration along the paths that the artificial ants have taken. If the ITSE is modest with the selected PID coefficients, the following ants attempt to complete their mission by winding these coefficients. Once the maximum tour has been completed, the roads with the highest value at the pheromone table, or particular PID coefficients, are recorded as a result of the optimization.

The speed control of BLDC motor comprises various components. Some of these components include PID controller, pulse width modulation (PWM) wave generator, switching, applying decoder logic for back EMF, ITSE, objective function for optimization algorithm, applying optimization algorithm to generate k_p, k_i, *and* k_d, Ha, Hb and Hc from Hall effect sensor, gate signal for insulated gate bipolar transistor (IGBT), etc. The input to PWM is taken as an input to the PWM wave generator as shown in Figure 4.

Figure 4
Block diagram of speed control of brushless DC (BLDC) motor



The line-to-line back EMF will be effectively estimated by Hall sensor after applying decoding logic that makes it possible for the detection of the position of the rotor. The error between reference speed and actual speed of the motor is applied to the PID controller. The controlling parameters of the PID controller will be effectively approximated using the optimization algorithm. The output from the PID control logic is fed into the PWM logic block. With the use of PWM and back EMF of the BLDC motor, the gate signal can be generated for the IGBT that is used in the three-phase inverter, and output from the inverter is fed into the BLDC motor.

The intelligent PID controller effectively tunes the parameter of it and eliminates steady-state error, reduces rise time, and decreases the overshoot so that the motor can effectively operate under varying load condition.

The PID controller receives the difference in motor speed between the reference speed and the motor's actual speed and applies the optimal PID parameters to the difference. PWM signal is produced using the PID block output signal. The gate signal for IGBT is then formed by switching a PWM signal with output logic created by a decoder block.

4. Results and Discussion

For this experiment, the parameters for the BLDC motor is tabulated. Table 1 shows the parameters value used in this experiment. Table 2 shows the parameters set for ACO configuration. In total, 50 ants used with the pheromone. The evaporation parameters are 0.95. The maximum allowable tour is 50.

Table 1
Brushless DC parameters for experiment

Parameters	Value
Stator phase resistance	0.1981 Ω
Stator line inductance	3.768 mH
Torque constant	1.225 Nm/A
Inertia	0.0055659 kg.m^2
Pole pair	4
Viscous damping	0.0004924 N.m.s

Table 2
Ant colony optimization (ACO) parameters

Objective function	Integral time square error
ACO parameters	No. of ants = 50
	Pheromone = 0.06
	Evaporation parameter = 0.95
	Positive pheromone = 0.2
	Negative pheromone = 0.3
	Max tour = 50
	Min value = -10
	Max value = 10

Figure 5 clearly depicts the output of this research with the ACO optimized PID tuning, which has perfect control of the BLDC motor. Red color shows the line of speed of BLDC and black color shows the reference speed. The Y axis represents the speed in rpm of BLDC motor and X axis represents the time in seconds. The reference speed and obtained actual speed are perfectly matching. It obtained the reference speed in 1.782 ms with the slew rate of 1.138 (/μs) and it has the low settling time 1.302 ms. However, Figure 6 shows the performance of the BLDC motor with traditional tuning approach. Where reference speed and obtained speed has difference. The rise time for this speed is 32.013 ms, which is too higher than ACO approach. This transient behavior of the PID tuning performance is observed and it seems traditional tuning never meets the reference speed as it has the infinite settling time. From these two figures, ACO optimization is more efficient than traditional PID tuning approach. Table 3 compares the head-to-head performance of optimized PID tuning by ACO and unoptimized tuning by classical approach.

Figure 5
Speed of brushless DC motor for optimized proportional–integral–derivative

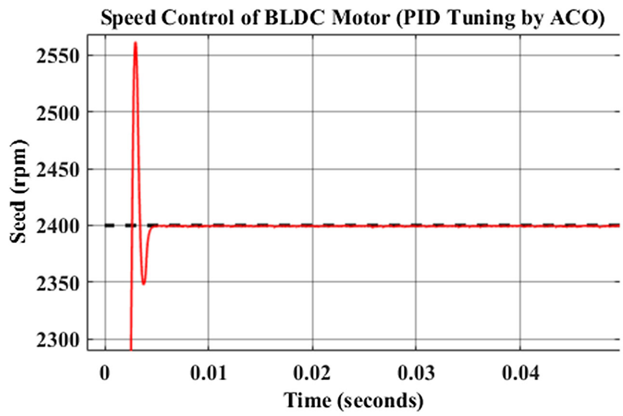
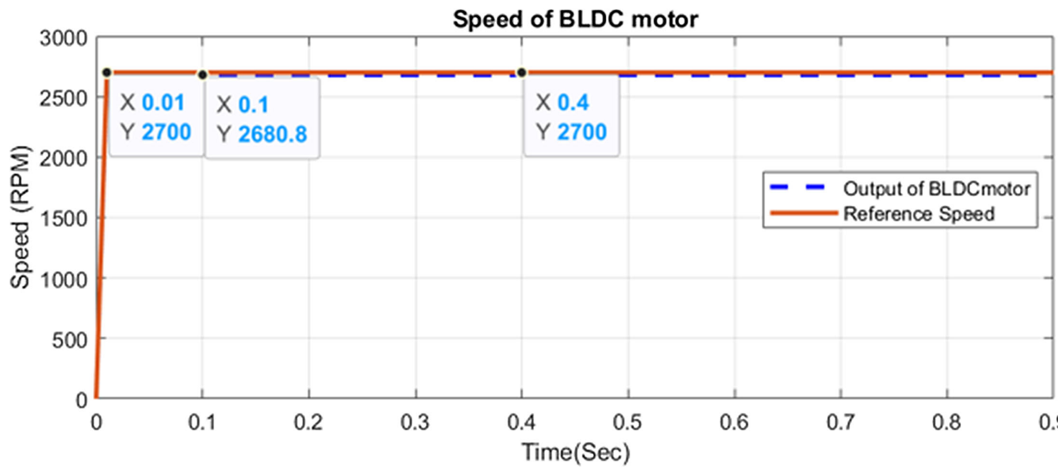


Table 3
Comparison between optimized and unoptimized PI

	Optimized PID	Unoptimized PID
PID parameters	$k_p = 118.2404$	$k_p = 60$
	$k_i = 8.7632$	$k_i = 5$
	$k_d = 0.047114$	$k_d = 0.9$
Rise time	1.782 ms	32.013 ms
Slew rate	1.138 (/μs)	60.884 (/ms)
Settling time	1.302 ms	_____
Overshoot	0.48%	−0.040%
Undershoot	1.97%	1.99%

Figure 6
Speed of brushless DC motor for unoptimized proportional–integral–derivatives



5. Conclusion

The novice and novel approach of bio-inspired metaheuristic algorithm is justified by this research work and study. The optimal controller is adjusted for the best performance of the system through the use of ACO algorithm. Proper PID controller tuning is ensured by this method, and hence this methodology, moreover, minimizes and reduces the value of steady-state error between the reference and the measured speed of the BLDC motor that has to be tracked. The transient behavior of the ACO-based PID tuning has the superior performance in terms of rise time and settling time with minimum undershoot. The control goal or objective is mainly to be pretty sure that the input shift is followed by the speed of the motor through the development of a suitable controller. The achievement and efficiency of the BLDC motor are elucidated by the results of the simulation through the use of ACO algorithm for the purpose of the speed control. Stability and faster response of the system is almost guaranteed by this algorithm. This research work justifies one of the quick response bio-inspired algorithms for the purpose of carrying out PID tuning. This research has great impact on modern control applications as it ensures the quality performance and capability of automatic tuning instead of time consuming, tedious task of PID tuning by classical approach.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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