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Optimization of PID Controller for Brushless DC Motor Based on Dung Beetle Algorithm

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ABSTRACT

The optimization of a PID controller for a Brushless DC (BLDC) motor is a crucial task to enhance its performance in various applications, including robotics, electric vehicles, and industrial systems. Traditional PID tuning methods often rely on manual or heuristic approaches, which may not yield the best performance regarding stability, response time, and robustness. This paper proposes the use of the Dung Beetle Optimizer Algorithm (DBO), a bio-inspired optimization method, to optimize the PID controller parameters for a BLDC motor. The Dung Beetle Algorithm mimics the foraging behavior of dung beetles, utilizing a population-based search strategy to explore the solution space efficiently. By optimizing the PID controller's proportional, integral, and derivative gains, the DBA seeks to minimize the error between the desired and actual motor performance, improving dynamic response, reducing overshoot, and enhancing system stability. In this paper, we aim to integrate the Dung Beetle algorithm (DBO) to tune the PID controller for a Brushless DC (BLDC) motor's speed control using Matlab simulation based on the objective function, which is the Integral Time Absolute Error (ITAE). A comparison of optimal performances (rise time, settling time, overshoot, peak response, and peak time) with a work that applied optimization by Genetic Algorithm and Simulated annealing on the same model and parameters of a Brushless DC motor. The results demonstrate that the DBO is the most effective approach to performance and convergence.

Keywords: Dung Beetle Optimizer, PID, Brushless DC motor, Speed control, ITAE.

INTRODUCTION

PID control (Proportional-Integral-Derivative) is a widely utilized control strategy in automation systems, particularly for controlling the behavior of motors, including Brushless DC (BLDC) motors. BLDC motors are favored for their efficiency, reliability, and precision in a variety of applications, such as robotics, electric vehicles, and industrial automation (Xue D. and C. YQChen, 2008; Rashid M. H., 2007; Kumar K. M.,2007; Kreith F. and Goswam D. Y.). The PID (Issa M., 1997; Xue D., 2017) controller plays a crucial role in regulating the speed, position, and torque of these motors, ensuring that they operate with high accuracy and stability.

In Brushless motor automation systems, the PID (Ekinci S., 2021; Papadopoulos K. G., 2015) controller adjusts the motor's speed and position by manipulating three components: the proportional term (P), which determines the immediate response to errors; the integral term (I), which addresses accumulated past errors; and the derivative term (D), which predicts future errors based on rate of change. By fine-tuning these parameters, the PID controller can ensure smooth, stable, and responsive motor performance.The Ziegler-Nichols (ZN) method is a traditional and widely adopted technique for tuning PID controllers. This method provides a systematic approach for setting the initial values of the PID parameters based on the system's dynamic response. The Ziegler-Nichols approach involves applying a step input to the system, increasing the proportional gain until the system oscillates, and then calculating the PID values from the observed oscillation characteristics. These tuned parameters serve as a good starting point for achieving a balanced trade-off between fast response and system stability.While the Ziegler-Nichols method has been a reliable method for PID tuning, modern advancements in automation control have led to the development of more sophisticated algorithms and optimization techniques. These newer methods offer improved efficiency and precision, automatically adjusting PID parameters based on real-time system feedback, reducing the need for manual tuning and enhancing the overall performance of BLDC motor control systems.

This work was achieved using MATLAB, a high-level interactive programming language, to perform simulations. Fothermore, it can use R Software (Haidas M. and Kerrache S., 2024) or others.

OBJECTIVES

The purpose of this paper is to explore the specific application method of a new metaheuristic algorithm, the Dung Beetle Optimizer (DBO) (Xue J. and Shen B, 2022), in order to design PID's parameters for controlling the speed of a Brushless DC motor using Matlab simulation.

LITERATURE REVIEW

To enhance the operational efficiency of Brushless DC motors and reduce both production and application costs, (Yuan Cheng et al., 2024) proposed an optimization approach based on the JAYA algorithm. Their method focuses on identifying the optimal parameters of a Brushless DC motor by leveraging electromagnetic structure parameter selection and efficiency calculation theories. Experimental results demonstrate that the improved JAYA algorithm achieves a lower average rank in unimodal function optimization, indicating stronger local optimization capabilities and improved stability. Furthermore, it shows robust search performance in navigating multiple local optima within multimodal functions.

(Qusay S. Kadhim et al., 2025) presented an optimal modeling approach for a Bearingless Brushless DC (BBLDC) motor, incorporating an advanced control strategy that utilizes a dual-loop scheme to manage both torque and suspension windings. This design effectively decouples the electromagnetic torque from the radial suspension forces. The study offers two key contributions: first, the optimal structural design of the BBLDC motor; second, the implementation of the Dragonfly Algorithm (DA) to enhance the motor's control system. This approach significantly reduces torque ripple, enables fast and accurate tracking, and eliminates overshoot. Comparative analyses confirm the superior performance of the proposed method over conventional Proportional-Integral (PI) controllers, showcasing faster response times, quicker convergence to steady state, and improved overall stability.

Neural network-based inverse system decoupling control offers a promising solution to address the nonlinear strong coupling characteristics of bearingless Brushless DC motors. However, this method often suffers from slow convergence and a tendency to become trapped in local extrema. To overcome these limitations, (Tao Tao and Lianghao Hua, 2023) introduced an Improved Particle Swarm Optimization (IPSO) algorithm to optimize the initial weights of the BP neural network inverse system. Comparative simulations between the conventional inverse system decoupling method and the proposed approach validate the enhanced performance and effectiveness of the IPSO-optimized strategy. Additionally, experimental results demonstrate that the proposed method achieves effective decoupling control in terms of both motor speed and radial displacement, including decoupling between the x- and y-axis radial components. These outcomes highlight the strategy's strong dynamic decoupling capability and improved system stability.

Brushless DC (BLDC) motors are widely used in industrial applications due to their high torque and efficiency. (Muhammed A. I. et al., 2019) proposed an optimally designed speed controller for BLDC motors utilizing a Genetic Algorithm (GA). This optimization technique was employed to determine the ideal Proportional–Integral–Derivative (PID) parameters. The study explored three controller design methods: traditional trial-and-error PID tuning, auto-tuning PID, and GA-based PID design. The PID controller's performance was evaluated using the Integral Absolute Error (IAE) and Integral Squared Error (ISE) criteria. By applying the genetic algorithm, optimal PID coefficients (K_p, K_i, and K_d) were identified, resulting in a hybrid GA-PID controller. Simulation results indicate that the GA-PID controller, particularly when optimized using the ISE objective function, outperforms other techniques in terms of time-domain performance metrics such as rise time, settling time, and percentage overshoot.

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(Singh S. Kr. et al., 2014) investigated and compared the effectiveness of various bio-inspired algorithms for optimizing PID controller performance in Brushless DC (BLDC) motor applications, as opposed to conventional tuning methods. The study employed Genetic Algorithms (GA), Multi-objective Genetic Algorithms (MOGA), and Simulated Annealing (SA) to optimize the PID controller parameters. These soft computing techniques aim to identify the optimal values of the PID gains (K_p, K_i, and K_d) to enhance the system's steady-state performance and minimize performance indices such as overshoot, rise time, and settling time. The optimized results obtained through GA, MOGA, and SA were compared to those from traditional tuning methods like the Ziegler–Nichols method and MATLAB's SISO Tool. Among the approaches, Simulated Annealing demonstrated superior results, delivering improved steady-state response and overall system performance.

METHODS

The research methodology for this work, titled "Dung Beetle Optimization Algorithm-Based PID Controller for Brushless DC Motor," is organized into several interconnected steps. The first step involves the mathematical modeling of the Brushless DC motor. Next, the Ziegler-Nichols method is used to design the PID parameters for the desired system's transfer function model. Finally, the methodology describes the Dung Beetle optimization algorithm and demonstrates its application in optimizing the PID parameters to achieve optimal performance in the speed control of the Brushless DC motor.

Mathematical Modeling of the Brushless Dc Motor

The mathematical modeling of a Brushless DC (BLDC) motor is crucial for analyzing its dynamics and designing an efficient control system. This model typically encompasses both the electrical and mechanical characteristics of the motor, including the armature, back electromotive force (EMF), torque, and other relevant parameters. The primary objective of the mathematical model is to accurately represent the motor's behavior, facilitating effective control and optimization.

The mathematical model of a BLDC motor consists of two main components: the electrical model and the mechanical model. **Figure 1** illustrates the equivalent electrical circuit of a Brushless DC motor.

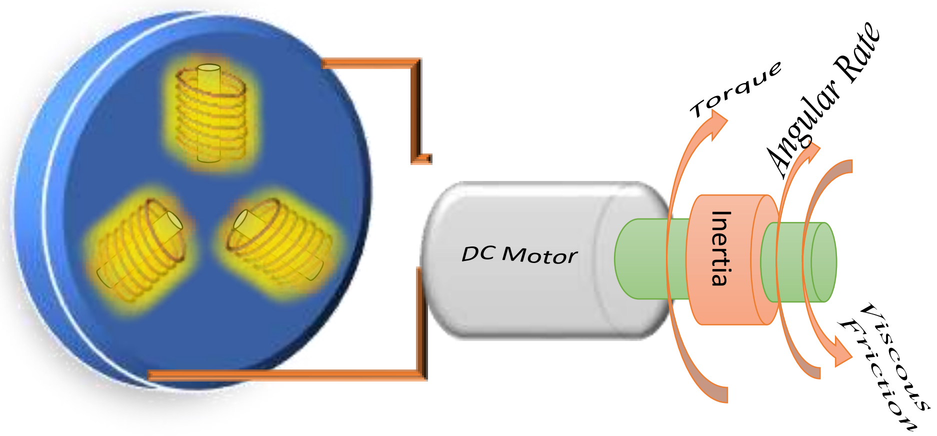

Figure 1. The schematic diagram of Brushless DC motor

The mechanical time constant of the BLDC motor is expressed by equation (1) (Patel Kr. V. S. et al., 2013; Singh S. Kr. et al., 2014):

$$\tau_m = \sum \frac{R\,J}{K_g K_t} = \frac{J \sum R}{K_g K_t} \quad (1)$$

The electrical (time constant) (Patel Kr. V. S. et al., 2013; Singh S. Kr. et al., 2014),

$$\tau_g = \sum \frac{L}{R} = \frac{L}{\sum R} \quad (2)$$

Mechanical constant (Patel Kr. V. S. et al., 2013; Singh S. Kr. et al., 2014)

$$\tau_m = \frac{J\ 3\ R}{K_g K_t} \tag{3}$$

Where,

$K_g = \left[\frac{N-m}{A}\right]$: The torque constant and $K_g = \left[\frac{v-secs}{rad}\right]$: The electrical torque (Patel Kr. V. S. et al., 2013)

Electrical constant (Patel Kr. V. S. et al., 2013)

$$\tau_g = \frac{L}{3\ R} \tag{4}$$

Hence, the equation for the BLDC motor is (Patel Kr. V. S. et al., 2013; Singh S. Kr. et al., 2014)

$$G(s) = \frac{\frac{1}{K_g}}{\tau_m\ \tau_g\ g^2 + \tau_m\ g + 1} \tag{5}$$

The BLDC motor considered in this paper is the EC 45 Flat (45 mm, 30 Watt) Brushless motor from Maxon Motors (Patel Kr. V. S. et al., 2013), with its parameters shown in **Table 1.**

Table 1. BLDC motor parameters used.

Maxon motor data	Unit	Value
Value at nominal voltage		
Nominal voltage	V	12.0
No load speed	Rpm	4370
No load current	mA	151
Nominal speed	Rm	2860
Nominal torque (max. continuous torque)	mNm	58
Nominal current (max. continuous current)	A	2.14
Stall torque	mNm	255
Starting current	A	10.0
Maximum frequency	%	77
Characteristics		
Terminal resistance phase to phase	Ω	1.2
Terminal inductance phase to phase	mH	0.56
Toque constant	mNm/A	25.5
Speed constant	rpm/V	37.4
Speed/torque gradient	Rpm/mNm	17.6
Mechanical time constant	Ms	17.1
Rotor inertia	gcm-2	92.5
Number of phases	-	3

So the values for K_e , τ_m and τ_g need to calculated to obtain the motor model (Patel Kr. V. S. et al., 2013; Singh S. Kr. et al., 2014).

Where,

$$\tau_g = \frac{L}{3.R} \tag{6}$$

$$\tau_g = \frac{0.56\times10^{-3}}{3.R} \tag{7}$$

$$\tau_g = 155.56 \times 10^{-6}\ Kgm^2 \tag{8}$$

But τ_m is a function of R, J, kg and Then

$$\tau_m = \frac{3.R.J}{K_g K_t} = 0.0171 \tag{9}$$

$$K_e = \frac{3\,R\,J}{\tau_m K_t} = 0.763\,\frac{v-secs}{rad} \quad (10)$$

Therefore, the G(s) becomes (Singh S. Kr. et al., 2014):

$$G(s) = \frac{13.11}{2.66\times10^{-6}.s^2+0.0171.s+1} \quad (11)$$

Ziegler Nichols PID's parameters

PID control is a type of feedback control system commonly used in industrial settings to manage and regulate various processes. The acronym PID refers to the three key components of the controller: Proportional, Integral, and Derivative. The proportional term K_p addresses the present error, the integral term K_i accounts for the cumulative error over time, and the derivative term K_d anticipates future errors by evaluating the rate of change of the error. By combining these three elements, a PID controller can precisely adjust the system's output to maintain a desired setpoint.

The Ziegler-Nichols method is a well-established technique in control systems engineering, commonly used to tune the parameters of PID controllers. Developed in the 1940s by John G. Ziegler and Nathaniel B. Nichols, it has become one of the most widely adopted approaches for improving the performance and stability of control systems (Ziegler J. G. and Nichols N. B, 1942; Dhanak M. R. and Xiros N. I., 2016).

Ziegler and Nichols proposed an experiment involving the step response of the open-loop plant model, where a tangent line is drawn to the response curve to extract the parameters k, L, T and $a = k*L/T$, which are illustrated in **Figure 2** (Xue D. et al., 2007; Maghfiroh H. et al, 2020).

Table 2 shows the guidelines to determinethe PID controller's parameters (K_p,K_i and K_d).

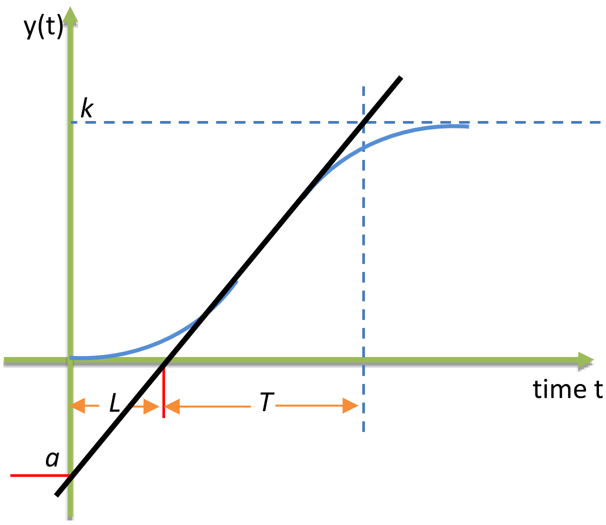

Figure 2: Ziegler-Nichol's graphical method

Table2. Ziegler–Nichols tuning formula

Controller type	From step response Kp	Ti	Td
P	1/a		
PI	0.9/a	3L	
PID	1.2/a	2L	L/2

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A Matlab simulation is developed to extract the PID controller's parameters based on Ziegler-Nichols's firstmethod, appplied to the Brushless DC motor's transfer function.The simulation result has given these parameters: L= 1.392602134237995e-04, and a = 0.007849858375472. Therefore, the PID controller's parameters are Kp = $1.52869\ x10^2$, Ki = $5.48861x10^5$ and Kd = $1.06443x10^{-2}$, which are represented in the closed loop for speed's control of the Brushless DC motor with reel parameters in **Figure 3**, and by ploting its unit step response in **Figure 4**.

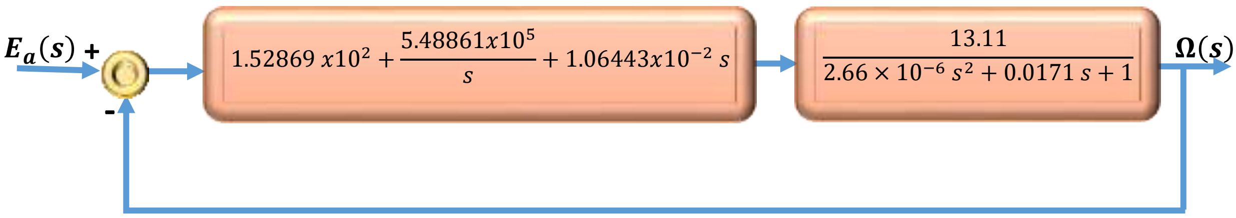

Figure 3. Brushless DC Motor control using PID

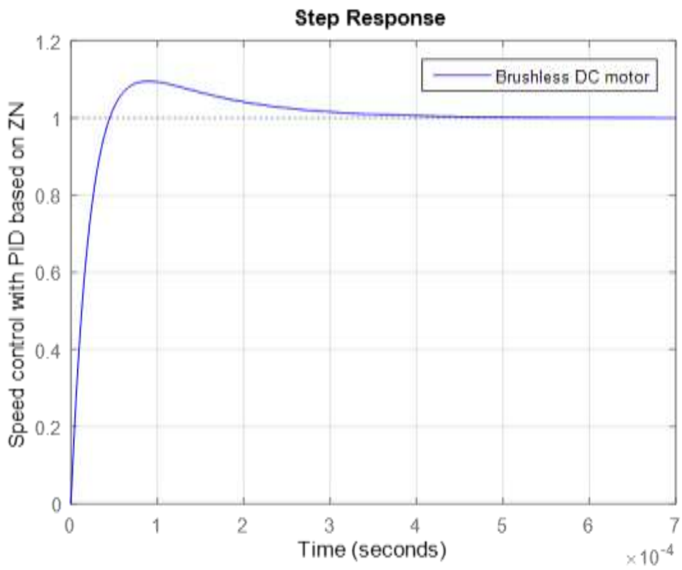

Figure 4. Brushless DC motor's speed control with PID based on ZN.

PID optimization by Dung Beetle Optimazer Algorithm

This study presents the Dung Beetle Optimizer (DBO) algorithm (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023), a unique population-based approach inspired by the dung beetle's behaviors, including ball-rolling, dancing, climbing, thieving, and reproduction. The algorithm balances local exploitation and global exploration to ensure a high convergence rate and optimal solution accuracy. Additionally, we assume that the intensity of the light source influences the dung beetle's trajectory. During the rolling process, the position of the ball-rolling dung beetle is updated and can be represented as (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$\begin{cases} Z_i(t+1) = Z_i(t) + \alpha \times \kappa \times Z_i(t-1) + b \times \Delta z \\ \quad where\ \Delta z = |Z_i(t) - Z^{\omega}| \end{cases} \tag{12}$$

Here, b is a constant value within the range (0, 1), while κ ∈ [0, 0.2] represents a constant reflecting the deflection coefficient. The variable t denotes the current iteration number. Zi(t) indicates the position of the iiith dung beetle at the tttth iteration. The global worst position is denoted as Zω, and variations in light intensity are represented by Δz. The natural coefficient α, which can take values of either -1 or 1, accounts for environmental factors such as wind or uneven terrain, which may cause dung beetles to deviate from their intended path (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023).

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If the dung beetle encounters an obstacle that prevents it from moving forward along its intended path, it will climb to the top of the dung ball and perform a dance to reposition itself. Consequently, the updated position of the BRDB is defined as follows (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$Z_i(t+1) = Z_i(t) + \tan(\Theta) \times |Z_i(t) - Z_i(t-1)| \quad (13)$$

This defection angle ϴ is located between [0, π].

Dung beetles hide their dung balls in safe locations to protect their offspring. To replicate the preferred egg-laying habitats of female dung beetles, a boundary selection technique called (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$\begin{cases} LB^s = \max(Z^* \times (1-F), LB) \\ UB^s = \min(Z^* \times (1+F), UB) \\ \quad where \quad F = 1 - \frac{t}{max-iter} \end{cases} \quad (14)$$

LB and UB represent the lower and upper limits of the optimization problem, respectively, while Z∗Z^*Z∗ denotes the current local best position, as illustrated in **Figure 5** (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023).

Once the spawning area is identified, female dung beetles select brood balls within this region for egg-laying. In each iteration of the DBO algorithm, each female dung beetle lays a single egg. Equation (13) indicates that the boundary range of the spawning area evolves dynamically, primarily influenced by the FFF value. Consequently, the position of the brood ball also changes dynamically throughout the iteration process, which is determined by (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$B_i(t+1) = Z^* + b_1 \times (B_i(t) - LB^8) + b_2 \times (B_i(t) - UB^8) \quad (15)$$

Here, b1 and b2 are two independent random vectors of size 1×D1, where D represents the dimensionality of the optimization problem. Bi(t) indicates the position of the iiith brood ball at the tttth iteration (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023).

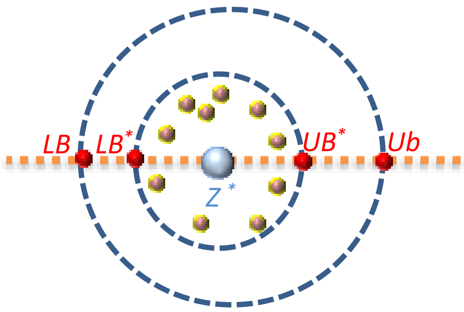

Figure 5. Boundary selection strategy conceptual model

Once fully grown, young dung beetles emerge from the ground in search of nourishment. The optimal foraging area for these dung beetles is defined as follows (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$\begin{cases} LB^b = \max(Z^b \times (1-F), LB) \\ UB^b = \min(Z^b \times (1+F), UB) \end{cases} \quad (16)$$

Where LBb and UBb represent the lower and upper boundaries of the optimal foraging territory, respectively, while Zb denotes the global optimal position. As a result, the little dung beetle's position is updated as follows (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023):

$$Z_i(t+1) = Z_i(t) + C_1 \times (Z_i(t) - LB^b) + C_2 \times (Z_i(t) - UB^b) \quad (17)$$

where $Z_i(t)$indicates the position information of the ith small dung beetle at the tth iteration, C1 represents a random number that follows normally distributed, and C2 denotes a random vector belonging to (0, 1).

As "dung thieves," some dung beetles steal dung balls from others. According to Equation (14), Zb represents the optimal feeding location. Consequently, as detailed below, the thief beetle's position is updated throughout the iteration process (Xue J. and Shen B, 2022; Jaiswal S. et al., 2023).

$$Z_i(t+1) = Z^b + S \times g \times (|Z_i(t) - Z^8|) + |Z_i(t) - Z^b| \quad (18)$$

where S is a fixed value, g is a normal-distributed random vector of size 1 × dim, and$Z_i(t)$reflects the ith thief's position at the tth iteration(Xue J. & Shen B, 2022; Jaiswal S. et al., 2023).

To enhance the performance of Brushless DC motor speed control, the Dung Beetle Optimizer (DBO) algorithm is proposed and applied to optimize the PID controller parameters. The objective function utilized is the Integral Time Absolute Error (ITAE), as presented in equation (19).

$$\text{ITAE} = \int t|e(t)|dt \quad (19)$$

Figure 6 illustrates the PID controller optimization diagram using the Dung Beetle algorithm to determine the optimal parameters (K_p,K_i,K_d). These parameters are then applied to simulate the final transient response of the Brushless DC motor's speed control.

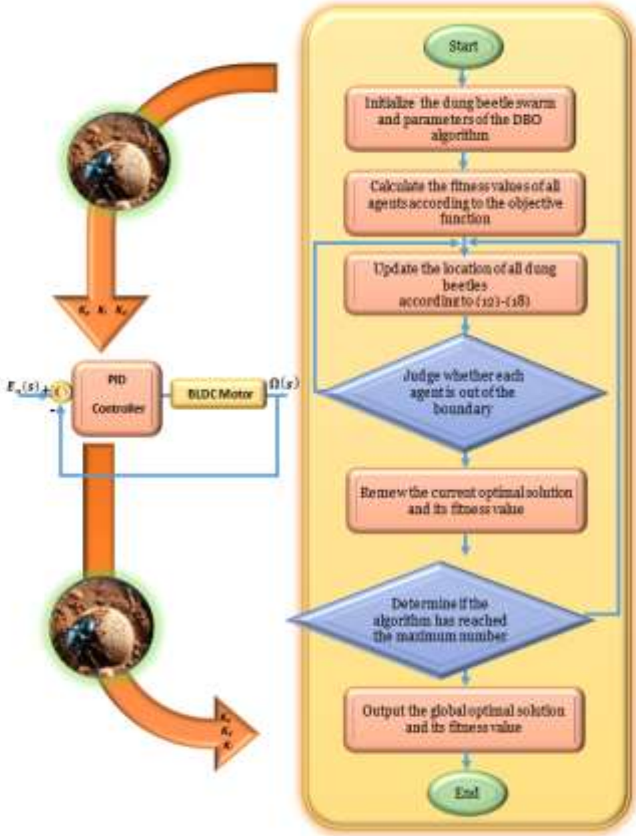

Figure 6. PID controller optimization diagram using Dung Beetle algorithm (Xue J. & Shen B, 2022; Zhang R. & Zhu Y., 2023)

RESULTS

According to the simulation created by MATLAB/SOFTWARE,the Dung Beetle Optimizer's parameters are shown in **Table 3**, where we have focused our work on three fitness functions, and desingningthe number of search agents, the maximum number of iterations and the PID parameters's lower and upper bands.The table 4 shows the simulation results of the optimal gain values of PID controller attained through using Dung Beetle Optimizer (DBO) for ISE, IAE and ITAE criteria, applied to the Brushless DC motor. **The Figure 7** and the table 5illustrate a comparisaon between differents transient responseswith their charachtiristics (rise time, settling time, overshoot, and peak response and peak time)for the study Brushless DC motor model,obtained by Ziegler Nichols with first method and the Dung Beetle Optimizer algorithm with the three proposed fitness functions. **Figure 8** presents a comparison between the various proposed methodson the convergence curves for the best score obtained.

Table3. Dung Beetle Optimizer's parameters

Fitness function	ITAE	
Number of search agents	50	
Maximum number of iterations	10	
	PID lower band	PID upper band
K_p	0.001	200
K_i	0.001	1520
K_d	0.0001	0.01

Table4. Gains of PID controller tuned by using Dung Beetle Optimizer

Parameters	DBO	GA (Singh et al., 2014)	SA (Singh et al., 2014)
K_p	25.5243895444894	5.0001	5.0424
K_i	1.48362306558138e+3	0.0039	0.0042
K_d	6.50018323179181e-3	5e-4	3.0454e-4

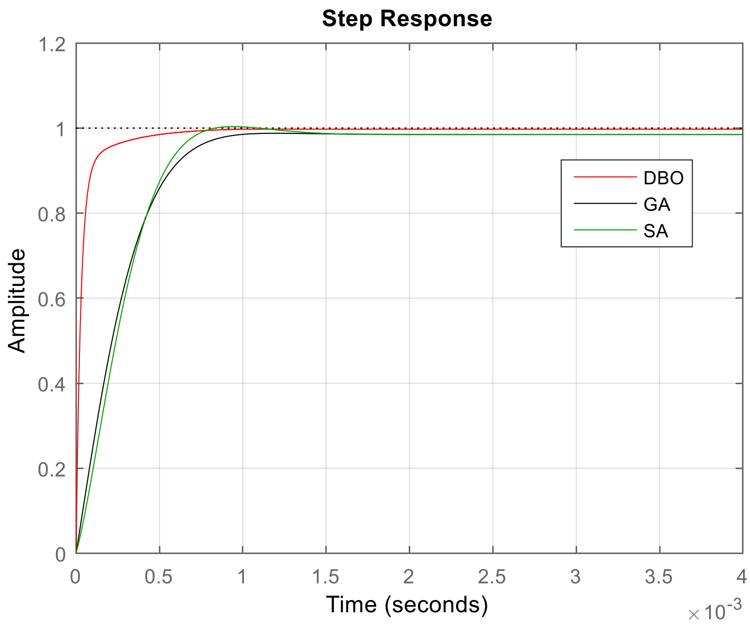

Figure 7. Step response of DBO-PID for Brushless DC motor system.

Table5. Time response chararateristics

Parameters	DBO	GA (Singh et al., 2014)	SA (Singh et al., 2014)
Rise Time	8.9838e-05	5.2893e-04	4.7767e-04
Settling Time	4.2281e-04	9.0019e-04	7.0512e-04
Overshoot	0 %	0 %	0 %
Peak Response	0.9973	0.9878	1.0036
Peak Time	9.8973e-04	0.0012	9.4084e-04

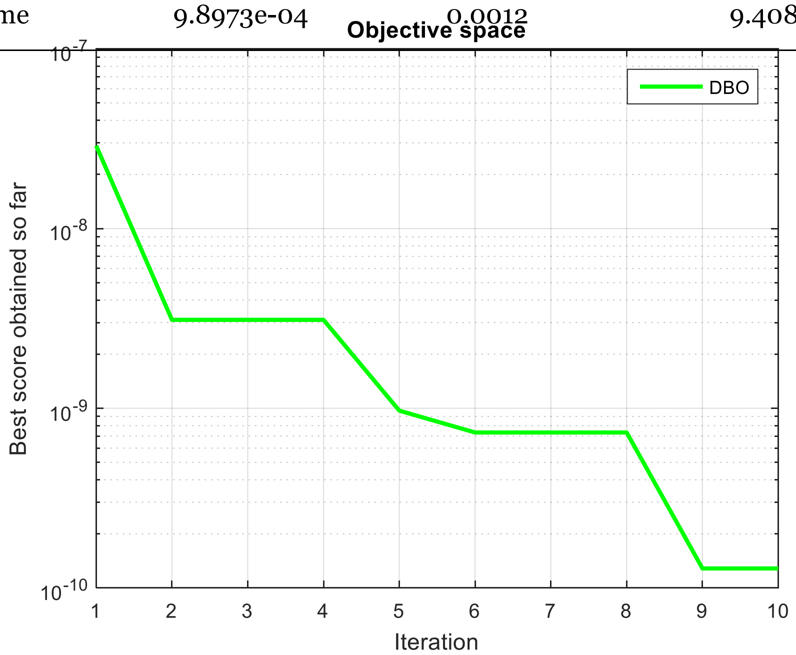

Figure 8. Controller's performance evaluation analysis

DISCUSSION

In this paper, the optimal PID speed controller parameters for a Brushless DC motor have been extracted using the Newton-Raphson Optimizer metaheuristic algorithm. This motor has been subjected to a thorough mathematical modeling process for the first stage, which includes an open loop simulation of the transient response. During the second phase, a decorticate modeling was entrusted to the Dung Beetle Optimizer algorithm (DBO), which is applied to tune the objective function of the desired model that combines PID controller and the Brushless DC motor in closed loop. A fitness function called the integral time absolute error (ITSES) has been tested and compared with other work (Singh et al., 2014), where it has given the best tuned PID's parameters, which are K_p = 25.5243895444894, K_i = 1.48362306558138e+3 and K_d = 6.50018323179181e-3. Therefore, the higher transient response performances has been confirmed by the characteristics obtained (rise time = 8.9838e-05, settling time = 4.2281e-04, overshoot = 0 %, peak response = 0.9973 and peak time = 9.8973e-04).

REFRENCES

[1] Dhanak M. R. and Xiros N. I., "Springer Handbook of Ocean Engineering," Springer Dordecht Heidelbeg London New York , 2016, doi:10.1007/978-3-319-16649-0.

[2] Dutta P. and Nayak S. K., Grey Wolf Optimizer Based PID Controller for Speed Control of BLDC Motor. Electrical Engineering and Technology, v. 16, p. 955–961, 2021, doi: 10.1007/s42835-021-00660-5.

[3] Ekinci S., Hekimog lu B. and Izci D., "Opposition based Henry gas solubility optimization as a novel algorithmfor PID control of DC motor," Engineering Science and Technology, an International Journal, vol. 24, pp. 331–342, 2021, doi: 10.1016/j.jestch.2020.08.011.

[4] Maghfiroh H., Nizam M. and Praptodiyono S., "PID optimal control to reduce energy consumption in DC-drive system," International Journal of Power Electronics and Drive System (IJPEDS), vol. 11, no. 4, pp. 2164–2172, Decembre 2020, doi: 10.11591/ijpeds.v11.i4.pp2164-2172.
[5] Haidas M. and Kerrache S., R-based neural networks decision model for water air cooler system", Indonesian Journal of Electrical Engineering and Computer Science, v. 35, n. 2, p. 1091-1098, 2024, doi: 10.11591/ijeecs.v35.i2.pp1091-1098.
[6] Issa M., "Enhanced Arithmetic Optimization Algorithm for ParameterEstimation of PID Controller," Arabian Journal for Science and Engineering , vol. 48, pp. 2191–2205, 2023, doi: 10.1007/s13369-022-07136-2.
[7] Irwin J. D., The Industrial Electronics Handbook, CRC Press LLC, 1997.
[8] Kumar K. M., "Dc Machines And Transformers," VIKAS Publishing. House. PVT Ltd , 2004.
[9] Kreith F. and Goswam D. Y., "The CRC Handbook of Mechanical Engineering," CRC Press, 2nd Ed, 2004.
[10] Muhammed A. I., Ausama KH. M. and Nashwan S. S., Optimal PID controller of a Brushless DC motor using genetic algorithm, International Journal of Power Electronics and Drive System (IJPEDS), v. 10, n. 2, p.822-830, 2019, doi: 10.11591/ijpeds.v10.i2.pp822-830.
[11] Papadopoulos K. G., "PID Controller Tuning Using the Magnitude Optimum Criterion," Springer International Publishing Switzerland, 2015, doi: 10.1007/978-3-319-07263-0.
[12] Papailiou K. O., Springer Handbook of Power Systems, Springer Nature Singapore Ltd, 2021, doi: 10.1007/978-981-32-9938-2.
[13] Patel KR. V. S. and Pandey A. K., Modeling and Performance Analysis of PID Controlled BLDC Motor and Different Schemes of PWM Controlled BLDC Motor, International Journal of Scientific and Research Publications, v. 3, n. 4, p. 2250-3153, 2013.
[14] Qusay S. Kadhim., Mahmood Swadi., Ali Jafer Mahdi ., Mohanad Azeez Joodi ., Firas Mohammed Tuaimah ., Moanes E., Mohammed ., Abbas Hafeth Abbas . And Mohamed Salem ., Optimum design of bearingless Brushless DC motor modeling with dual loop controller using dragonfly optimizers, e-Prime - Advances in Electrical Engineering, Electronics and Energy 11 (2025) 100942, https://doi.org/10.1016/j.prime.2025.100942.
[15] Rashid M. H., "Power Electronics Handbook: Devices, Circuits and Applications," Academic Press in an imprint of Elsevier, 2007.
[16] Shi J., MI Q., Cao W. and Zhou L., Optimizing BLDC motor drive performance using particle swarm algorithm-tuned fuzzy logic controller, SN Applied Sciences, v. 4, n. 293 , 2022, doi: 10.1007/s42452-022-05179-6.
[17] Singh S. KR., Katal N. and Modani S. G., Optimization of PID Controller for Brushless DC Motor by using Bio-inspired Algorithms, Research Journal of Applied Sciences, Engineering and Technology, v. 7, n. 7, p. 1116-1122, 2014, doi: 10.19026/rjaset.7.395.
[18] Tao Tao. and Lianghao Hua., Decoupling control of bearingless Brushless DC motor using particle swarm optimized neural network inverse system, Elsevier, Volume 31,February2024, 100952, https://doi.org/10.1016/j.measen.2023.100952.
[19] Xue D., "Fractional Order Control System Fundamentals and Numerical Implementations," Walter de Gruyter GmbH, Berlin/Boston, 2017, doi: https://doi.org/10.1515/9783110497977.
[20] Xue D., C. YQChen, "Solving Applied Mathematical Problems with MATLAB," CRC Press, 1st Ed, 2008.
[21] Xue D., CHEN Y. and ATHERTON D. P., Linear Feedback Control: Analysis and Design with MATLAB, Singapore. SIAM, 2007, doi: 10.1137/1.9780898718621.
[22] Xue J. and Shen B., "Dung beetle optimizer: a new meta-heuristic algorithm for global optimization," The Journal of Supercomputing, 2022, doi.org/10.1007/s11227-022-04959-6.
[23] Yuan Cheng, Xueli Lyu and Shasha Mao., Optimization design of Brushless DC motor based on improved JAYA algorithm, Scientific Reports, 14, 5427, 2024, https://doi.org/10.1038/s41598-024-54582-z.
[24] Yedamale P., "Brushless DC motor fundamentals. Microchip Technology Incorporated, 2003.
[25] Ziegler J. G. and Nichols N. B., Optimum Settings for Automatic Controller, Trans. ASME , v. 64, n. 8, p. 759–768, 1942.