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Performance Evaluation of Osprey Optimization Algorithm-Based Proportional Integral Derivative Controller for Speed Control of a Brushless Direct Current Motor

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ABSTRACT

Owing to the diversity of applications, speed regulation of a Brushless Direct Current (BLDC) motor is essential to achieve the best performance of the motor. In this paper, an appropriately tuned controller such as Proportional Integral Derivative (PID) is employed to achieve effective speed control of the motor. In tuning the parameters of the PID controller, conventional techniques often pose great difficulties due to the non-linearity often exhibited by DC motors. As a solution, metaheuristic optimization techniques are adopted to optimally tune the PID controller parameters for optimal performance of the BLDC motor in terms of speed. Thus, the Osprey Optimization Algorithm (OOA) tuned PID controller (OOA-PID) was used to achieve better performance of BLDC motor speed. Kirchoff's Voltage Law and Newton's second law of motion were employed to derive the BLDC motor mathematical model. The PID mathematical equation was also described and an optimization model was formulated using the Integral of Time Multiplied Absolute Error (ITAE) and optimized using OOA. The performance of the OOA-PID controller with BLDC motor was evaluated using performance metrics such as rise time, settling time, overshoot and steady state error. Simulations were done using MATLAB (R2021b). Simulation result shows that an OOA-PID controller gave better response when compared with existing Ziegler Nichols PID (ZN-PID) used for the same purpose.

INTRODUCTION

Direct Current (DC) motors are widely utilized in industry due to their good control response, wide speed control range, and widespread application in systems with high control needs, such as rolling mills, double-hulled tankers, and high precision digital tools among others (Pathak and Tripathy, 2018). Compared to conventional DC motors, Brushless DC motors (BLDC) are more frequently employed in industrial applications and instruments because of their appealing properties like high efficiency, high torque, tremendous speed, low noise, small volume, and prolonged life (Ibrahim *et al*., 2019).

A BLDC motor is an electric motor without a commutator or slip ring and can be powered by either direct current (DC) or alternating current (AC) depending on their design. Using electromagnetic principles, the BLDC motor transforms electrical energy into mechanical energy. The attraction or repulsion between magnetic poles is the basis for motor operation. Torque and speed control for BLDC motors are very important. To modify the motor's input electric power and achieve the necessary speed, speed control is necessary

(Singh *et al*., 2018). Additionally, speed control is crucial in sensitive applications where the motor speed must be exact and stable. This calls for more effective dynamic control that focuses on the motor's transient reaction and steady-state response (Ahmed *et al*., 2020). The PID controller is a feedback control loop mechanism that determines an "error" value as the difference between a measured process variable and a desired set point; the error is reduced by modifying the process control inputs. Three elements such as proportional, integral, and derivative elements are connected in parallel to form a PID controller (Ahmed *et al*., 2020).

The proportional integral derivative (PID) controller emerged as a feasible option among several regulating techniques due to its simple design and dependable performance across a broad operating range (Jalilvand *et al*., 2011). One major conventional tuning method for PID controllers is the use of Ziegler-Nichols. It is a conservative tuning method that is preferred for control loops at which the measure of oscillation provides ¼ decay ratio and the corresponding large and undesirable overshoots for set point changes. The approach put out by Ziegler and Nichols is based on registering the system's open-loop step response, which is defined by two parameters (Hassan *et al*., 2018). In this paper, the performance of the BLDC motor in terms of speed was examined in which OOA was used to tune the parameters of PID controller.

MATERIAL AND METHODS.

The material and methodology involved in this work are as described in the subsequent sections.

BLDC motor modeling

BLDC motor is like a conventional DC motor except there are three phases in BLDC motor, the BLDC motor output speed is regulated through ways of a three-phase pulse-width modulation inverter. The BLDC motor equations can be expressed as equations (1) to (6) (Ibrahim *et al*., 2019). The schematic illustration of the BLDC motor is shown in Figure 1. The Simulink model block of the BLDC motor was developed with the Simulink interface of MATLAB R2021b using Equations (1) to (6)

$$v_{app}(t) = L\frac{di(t)}{dt} + R \times i(t) + v_{emf}(t) \quad (1)$$

$$V_{emf} = k_b \times w(t) \quad (2)$$

$$T(t) = k_t \times i(t) \quad (3)$$

$$T(t) = J\frac{dw(t)}{dt} + D \times w(t) \quad (4)$$

$$G(s) = \frac{w(s)}{V(s)} = \frac{k_t}{LJs^2 + (LD + RJ)s + k_t k_b} \quad (5)$$

where:

V_{app} (t) = Applied voltage V_{app} (t)

w(t) = Motor speed

V_{emf} (t) = Back electromotive force

i(t) = Motor Current

L = Inductance of stator

T = Motor torque

D = Viscous coefficient

J = moment of inertia

K_b = Back electromotive force

K_t = motor torque constant

The BLDC motor transfer function is calculated as:

$$G(s) = \frac{w(s)}{V(s)} = \frac{k_t}{LJs^2 + (LD + RJ)s + k_t k_b} \quad (6)$$

PID controller modeling

Proportional Integral Derivative (PID) controllers are widely used in industrial control systems because of the reduced number of parameters to be tuned. They provide control signals that are proportional to the error between the reference signal and the actual output (proportional action), to the integral of the error (integral action), and to the derivative of the error (derivative action). It can be expressed as Equation (7) (Kanojiya and Meshram, 2012). The conventional PID controller system block diagram is shown in Figure 2.

$$U(t) = \left[K_p e(t) + \frac{1}{K_i}\int_o^t e(\tau)d\tau + K_d \frac{d}{dt} e(t)\right] \quad (7)$$

where $K_p, K_i,$ and K_d are the parameters to be tuned, $e(t)$ is the input signal and $U(t)$ is the output signal.

The corresponding transfer function is given as Equation (8)

$$K(s) = \left[1 + \frac{1}{k_i(s)} + K_d(s)\right] \quad (8)$$

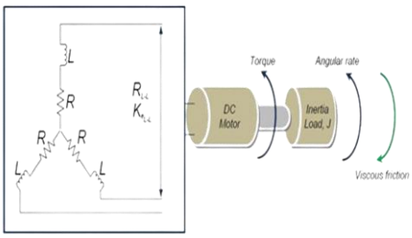

Figure 1: Schematic diagram of BLDC motor (Ahmed *et al*., 2020)

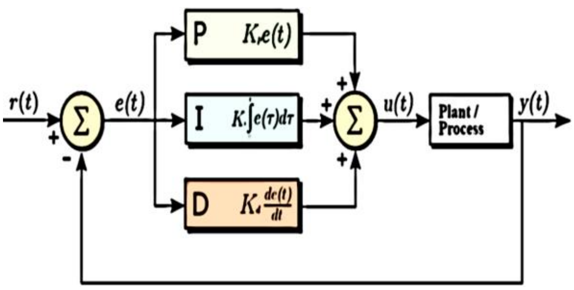

Figure 2: PID Controller System Block Diagram (Ahmed *et al*., 2020)

OOA mathematical modeling

Osprey optimization algorithm is a novel optimization algorithm that has the advantage of maintaining the balance between exploration and exploitation and fast convergence over other competitor algorithms. Its mathematical model is presented as follows (Dehghani and Trojovský, 2023).

The process of updating the position of ospreys is in two phases, these are exploration and exploitation phases. In this section, the initialization of OOA is described first, then updating the position of ospreys based on the simulation of natural osprey behaviors is presented.

Initialization:

The proposed OOA is a population-based method that may locate a workable solution based on the search power of its population members in the problem-solving domain via a repetition-based method. Each osprey can be thought of as a potential solution to the issue, represented mathematically by a vector. The OOA population can be represented by a matrix following Equation 9. Equation 10 is used to randomly initialize the ospreys' location in the search space before OOA implementation begins.

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}_{N\times m} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,m} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,m} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ x_{N,1} & \cdots & x_{N,j} & \cdots & x_{N,m} \end{bmatrix}_{N\times m} \quad (9)$$

$$x_{i,j} = lb_j + r_{i,j}.(ub_j - lb_j), i = 1,2,\ldots,N, j = 1,2,\ldots,m \quad (10)$$

where X is the population matrix of ospreys' locations, X_i is the ith osprey (a candidate solution), $x_{i,j}$ is its jth dimension (problem variable), N is the number of ospreys, m is the number of problem variables, $r_{i,j}$ are random numbers in the interval [0, 1], lb_j, and ub_j are the lower bound and upper bound of the jth problem variable respectively.

The objective function can be evaluated, and the evaluated values for the objective function can be represented using a vector in accordance with Equation 11.

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N\times 1} \quad (11)$$

where F is the vector of the objective function values and F_i is the obtained objective function value for the ith osprey.

Phase 1: Position identification and hunting the fish (exploration)

The simulation of the natural behavior of ospreys in hunting serves as the basis for the first phase of the OOA population update model. By significantly altering the position of the osprey in the search space as a result of modeling the osprey attack on fish, OOA is better able to determine the ideal location and flee from local optima. For each osprey, the placements of other ospreys in the search space with greater objective function values are referred to in OOA design as underwater fishes. The set of fish for each osprey is given as Equation 12

$$FP_i = \{X_k | k \in \{1,2,\ldots,N\} \wedge F_k < F_i\} \cup \{X_{best}\} \quad (12)$$

where FP_i is the set of fish positions for the ith osprey and X_{best} is the best candidate solution (the best osprey). An attack on one of these fish occurs when the osprey, at random, finds its location. A new position for the associated osprey is determined using Equations 13-14 based on the simulation of the osprey's progress toward the fish. According to Equation 15, the osprey will take the new location if it increases the value of the objective function and replaces the old position.

$$x_{i,j}^{p1} = x_{i,j} + r_{i,j}.\left(SF_{i,j} - I_{i,j}.x_{i,j}\right) \quad (13)$$

$$x_{i,j}^{p1} = \begin{cases} x_{i,j}^{p1}, & lb_j \le x_{i,j}^{p1} \le ub_j; \\ lb_j & x_{i,j}^{p1} < lb_j \\ ub_j & x_{i,j}^{p1} > ub_j \end{cases} \quad (14)$$

$$X_i = \begin{cases} X_i^{p1} & F_i^{p1} < F_i; \\ X_i & else, \end{cases} \quad (15)$$

where X_i^{p1} is the new position of the ith osprey based on the first phase of OOA, $x_{i,j}^{p1}$ is its j th dimension, F_i^{p1} is its objective function value, SF_i is the selected fish for ith osprey, $SF_{i,j}$ is the its jth dimension, $r_{i,j}$ are random numbers in the interval [0, 1], and $I_{i,j}$ are random numbers from the set {1,2}.

Phase 2: Carrying the fish to the suitable position (exploitation)

The osprey's position in the search space is slightly altered as a result of the modeling of carrying the fish to the proper position, which increases the OOA's exploitation power in the local search and causes convergence towards better solutions close to the discovered solutions.

In the OOA design, a new random position for each member of the population is first generated as a "suitable position for eating fish" using Equation 16-17. Then, if the value of the objective function is improved in this new position, it replaces the previous position of the corresponding osprey according to Equation 18 given below:

$$x_{i,j}^{p2} = x_{i,j} + \frac{lb_j + r_{i,j}.(ub_j - lb_j)}{t}, i = 1,2,\ldots,N, j = 1,2,\ldots,m, t = 1,2,\ldots,T \quad (16)$$

$$x_{i,j}^{p2} = \begin{cases} x_{i,j}^{p2}, & lb_j \le x_{i,j}^{p2} \le ub_j; \\ lb_j & x_{i,j}^{p2} < lb_j \\ ub_j & x_{i,j}^{p2} > ub_j \end{cases} \quad (17)$$

$$X_i = \begin{cases} X_i^{p2} & F_i^{p2} < F_i; \\ X_i & else, \end{cases}$$

where X_i^{p2} is the new position of the ith osprey based on the second phase of OOA, $x_{i,j}^{p2}$ is its jth dimension, F_i^{p2} is its objective function value, $r_{i,j}$ are random numbers in the interval [0, 1], t is the iteration counter of the algorithm, and T is the total number of iterations (Dehghani and Trojovský, 2023).

OOA for optimal PID controller parameters

The PID control structure is shown in Figure 2. The optimal value obtained from OOA was used as the PID parameters (K_p, K_i, and K_d) the tuned PID controller was used to control the speed of the BLDC motor. The following are the procedural steps for the developed OOA-PID, which estimated the optimum PID controller parameters (such as K_p, K_i, and K_d).

Step 1: Input the BLDC parameters, problem information (variables, objective function, and constraints (lb, ub)), population size (N) and the total number of iterations (T).

Step 2: Run the BLDC motor model without the PID controller to get the base case for comparison

Step 3: Generate the initial population matrix at random using equations 19 and 20. Each column represents the PID parameters.

$$K_{PID} = \begin{bmatrix} K_{1,P} & K_{1,I} & K_{1,D} \\ \vdots & \vdots & \vdots \\ K_{i,P} & K_{i,I} & K_{i,D} \\ \vdots & \vdots & \vdots \\ K_{N,P} & K_{N,I} & K_{N,D} \end{bmatrix} \quad (19)$$

$$k_{i,j} = lb_j + r_{i,j}.\left(ub_j - lb_j\right), i = 1,2,\ldots,N, j = 1,2,3 \quad (20)$$

where K_{PID} is the population matrix of ospreys' locations that represents the PID parameters, $r_{i,j}$ are random numbers in the interval [0, 1]. lb_j, and ub_j are the lower bound and upper bound of the jth problem variable respectively.

Step 4: Evaluate the objective function using Equation 21 and find the initial best fitness

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} F\left(K_{PID,1}\right) \\ \vdots \\ F\left(K_{PID,i}\right) \\ \vdots \\ F\left(K_{PID,N}\right) \end{bmatrix}_{N\times 1} \quad (21)$$

where F is the vector of the objective function values and F_i is the obtained objective function value for the ith osprey

Step 5: Update fish positions set for the ith osprey using Equation 22 below:

$$FP_i = \left\{K_{PID,x} \mid x \in \{1,2,\ldots,N\} \wedge F_x < F_i\right\} \cup \left\{K_{PID,best}\right\} \quad (22)$$

where FP_i is the set of fish positions for the ith osprey and $K_{PID,best}$ is the best candidate solution (the best osprey).

Step 6: Determine the selected fish by the ith osprey at random and calculate the new position of the ith osprey based on the first phase of OOA using Equation 23:

$$k_{i,j}^{p1} = k_{i,j} + r_{i,j}.\left(SF_{i,j} - I_{i,j}.k_{i,j}\right) \quad (23)$$

Step 7: Check the boundary conditions for the new position of osprey members using Equation 24:

$$k_{i,j}^{p1} = \begin{cases} k_{i,j}^{p1}, & lb_j \le k_{i,j}^{p1} \le ub_j; \\ lb_j & k_{i,j}^{p1} < lb_j \\ ub_j & k_{i,j}^{p1} > ub_j \end{cases} \quad (24)$$

Step 8: Update the ith osprey using Equation 25:

$$K_{PID,i} = \begin{cases} K_{PID,i}^{p1} & F_i^{p1} < F_i; \\ K_{PID,i} & else, \end{cases} \quad (25)$$

Step 9: Calculate the new position of the ith osprey based on the second phase of OOA using Equation 26 and check the boundary conditions for the new position of OOA members using Equation 27:

$$k_{i,j}^{p2} = k_{i,j} + \frac{lb_j + r_{i,j}.\left(ub_j - lb_j\right)}{t}, i = 1,2,\ldots,N, j = 1,2,3, t = 1,2,\ldots,T \quad (26)$$

$$k_{i,j}^{p2} = \begin{cases} k_{i,j}^{p2}, & lb_j \leq k_{i,j}^{p2} \leq ub_j; \\ lb_j & k_{i,j}^{p2} < lb_j \\ ub_j & k_{i,j}^{p2} > ub_j \end{cases} \quad (27)$$

Step 10: Update the ith member Equation 28:

$$K_{PID,i} = \begin{cases} K_{PID,i}^{p2} & F_i^{p2} < F_i; \\ K_{PID,i} & else, \end{cases} \quad (28)$$

Step 11: While the end criterion (that is the number of iterations) is less than the maximum number of iterations (N), Repeat Step4 to Step10, else go to Step12

Step 12: Display the best solution and position which is the minimum Integral of Time multiplied by Absolute Error (ITAE) and optimal PID parameters (K_P, K_I, K_D).

Step 13: Stop.

Objective Function Value

To present a fair comparison with existing works in the literature, the Integral of Time multiplied Absolute Error (ITAE) was adopted in this work as an objective function. ITAE is expressed in Equation 29 (Hekimoglu, 2019).

$$ITAE = \int_0^{t_{sim}} t * |e(t)| \quad (29)$$

where $e(t)$ is the error signal that is the difference between reference and actual angular speeds, and t_{sim} is the simulation time. When the ITAE objective function is minimized, the transient response of the DC motor speed control system is improved in terms of maximum overshoot, settling time and rise time.

The constraints that need to be satisfied in the optimal tuning of PID controller parameters using OOA are given in Equations (30) to (32) (Hekimoglu, 2019).

$$K_P^{min_P{}_P^{max}} \quad (30)$$

$$K_I^{min_I{}_I^{max}} \quad (31)$$

$$K_D^{min_D{}_D^{max}} \quad (32)$$

where K_P, K_I and K_D are the values of the PID parameters.

RESULTS AND DISCUSSIONS

The optimal tuning of PID for the speed control of a Brushless DC (BLDC) motor using the Osprey Optimization Algorithm (OOA) was conducted in this work to enhance the satisfactory performance of BLDC motors. The mathematical models of the BLDC motor, PID controller and OOA were developed and the simulation was carried out in MATLAB environment (R2021b) to represent their real-life design to be able to evaluate their performances. The simulation parameters used in this work are presented in Table 1. The results from this simulation are presented and discussed in the sections below. The open loop response of the system without a controller is presented in Figure 3. The step information of the system response in terms of the performance metrics is presented in Table 3.

Table 1: Simulation Parameters

Parameters	Value
Brushless Motor Parameters	
Stator resistance (*R*)	11.20 *Ω*
Inductance of the stator (*L*)	0.0520 *H*
Motor torque constant (K_t)	0.0316 *kgm/A*
Back electromotive force constant (K_b)	0.0316 *V/rad/s*
Moment of inertia (*J*)	1e-3 $Kgms^2/rad$
Viscous coefficient (*D*)	1e-4 $Kgms^2/rad$

Following the open loop response, it can be observed that the steady-state response of the simulated motor is 31.6 rpm, it took 24.64 seconds for the motor to rise from 10% to 90% of its steady-state response (i.e. from 3.16 to 28.44 rpm) and its settling time is 43.89 seconds. It can also be observed that the system oscillates between 28.62 and 31.64 rpm for 43.89 seconds before reaching its steady state. This result shows that, though the system had zero overshoot and undershoot, it took long to reach its steady state.

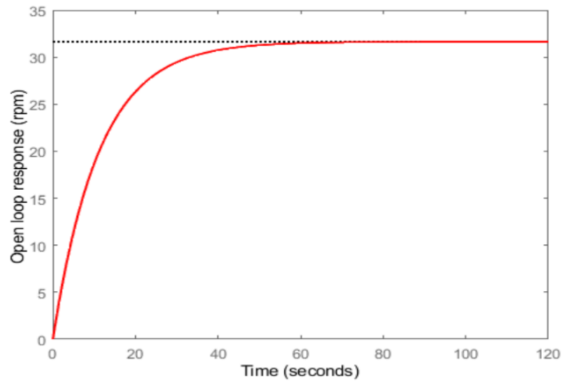

Figure 3: Open Loop Response of Brushless DC Motor.

OOA-PID Controller for the speed control of Brushless DC motor

With OOA-tuned PID for the speed control of the Brushless DC motor to enhance optimum performance.

Table 3: Step Information Open Loop Response of Brushless DC Motor

Parameter (Unit)	Value
Rise time (second)	24.6433
Settling time (second)	43.8852
Settling Minimum (rpm)	28.6222
Settling Maximum (rpm)	31.6447
Overshoot	0
Undershoot	0
Peak	31.6447

The resulting optimized parameters are presented in Table 4a. The step information of the response is presented in Table 4b and the closed-loop response of the Brushless DC motor with PID controller is presented in Figure 4. The rise time and settling time of the OOA-PID controller is 1.32 and 2.43 seconds respectively. This implies that compared to the system without a controller, the rise to is reduced from 24.64 seconds to 1.32 seconds (approximately 95% reduction). Not only that, the time it takes the system to reach its steady state was also reduced from 43.89 to 2.43 seconds, which is around a 94% reduction. The overshoot and undershoot of the system are also zero, this implies that the performance of the proposed controller adds no overshoot or undershoot to the operation of the system.

ZN-PID Controller for the speed control of Brushless DC motor

The optimal tuning parameters obtained through the ZN technique are presented in Table 5a. The ZN-tuned PID (ZN-PID) was also used to control the brushless DC motor's speed and the step information presented in Table 5b. The resulting closed-loop response is presented in Figure 5.

Table 4a: Optimal Parameters of PID controller using OOA

Parameter	Value
Proportional (K_p)	0.7767
Integral (K_i)	0.0680
Derivative (K_d)	0.1736

The resulting closed-loop response is presented in Figure 5. The rise time, settling time and percentage overshoot are 1.21 seconds, 6.71 seconds and 7.04%. These show that ZN-PID provides a significant improvement in the performance of the brushless DC motor, however, a 7.04% overshoot was introduced, which calls for another concern.

Table 4b: Step Information of the Brushless DC Motor with OOA-PID controller

Parameter (Unit)	Value
Rise time (second)	1.3150
Settling time (second)	2.4258
Settling Minimum (rpm)	0.9000
Settling Maximum (rpm)	0.9994
Overshoot	0
Undershoot	0
Peak	0.9994
Steady-state error	0.3198

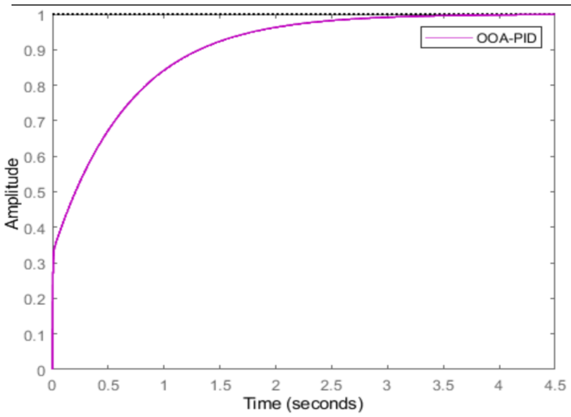

Figure 4: Closed Loop Response of Brushless DC Motor with OOA-PID Controller

Although the overshoot is not much, however, when used in a system sensitive to a slight change in speed, the effect will be detrimental.

Comparison between OOA-PID and ZN-PID

Table 6 shows the system characteristics for both the OOA-PID and the ZN-PID. Figure 6 shows the comparison between the step response of the BLDC motor using the OOA-PID controller and the ZN-PID controller. In percentage overshoot, the brushless motor with ZN-PID had 7.04%, while the motor with OOA-PID had zero overshoot

Table 5a: Optimal Parameters of PID controller using ZN

Parameter	Value
Proportional (K_p)	0.7357
Integral (K_i)	0.3282
Derivative (K_d)	0.4123

Table 5b: Step Information of the Brushless DC Motor with ZN-PID controller

Parameter (Unit)	Value
Rise time (second)	1.2069
Settling time (second)	6.7146
Settling Minimum (rpm)	0.9000
Settling Maximum (rpm)	1.0704
Overshoot	7.0446
Undershoot	0
Peak	1.0704
Steady state error	1.3047

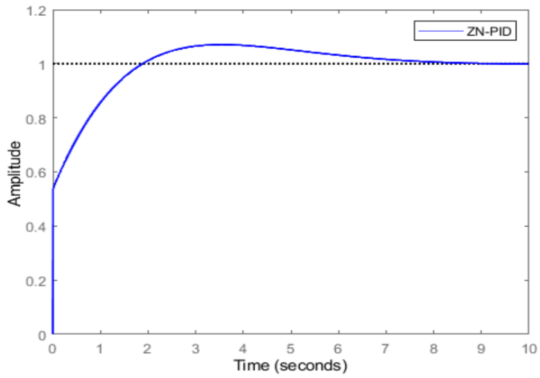

Figure 5: Closed Loop Response of Brushless DC Motor with ZN-PID Controller

CONCLUSION

In this study, the performance of BLDC motor speed was investigated using an Osprey 0ptimization Algorithm-based PID controller.

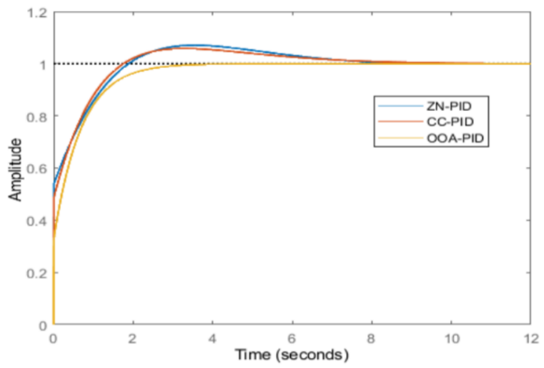

Figure 6: Step Response of Brushless DC Motor with OOA-PID and ZN-PID Controller

The ITAE was taken as the objective function to study the rise time, settling time, overshoot and steady-state error of a BLDC motor. The OOA-PID controller was applied to a BLDC motor. The results show that with the OOA-PID controller, the motor performed significantly better. Thu**s,** OOA can be used to optimally tune the parameters of the PID controller for the speed control of the brushless DC motor for its optimum performance.

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