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# Enhanced Speed Control for BLDC Motors using WOA-Integrated PID Controller Optimization

Chaithanya Reddy P. V
Department of Electrical and Electronics Engineering
NITTTR,Chennai
Lecturer in EEE, GPT URAVAKONDA
Anantapur ,India

Dr.R.Suja Mani Malar
Department of Electrical and Electronics Engineering
NITTTR,Chennai
Associate professor & Head DCDCB
Chennai , India

**ABSTRACT :** In electrical engineering, Brushless Direct Current (BLDC) motors are frequently used in mechanical applications because of their effectiveness, strong torque, and small design. Nevertheless, reaching peak performance and making accurate adjustments to parameters can be difficult when using a simple, customized Proportional Integral Derivative (PID) controller. In the past, speed control typically included adjusting crucial factors like voltage, and current. However, manual speed regulation has drawbacks, including being time-consuming, susceptible to human error, and lacking scalability. Different traditional models have tried to enhance speed control efficiency with Artificial Intelligence (AI) but face challenges in improving Rise Time, Settling Time, Maximum Overshoot, and overall efficiency. **A proposed approach to address this problem involves the implementation of a developed model using the Enhanced Whale Optimization Algorithm- Tuned PID (EWOA-TPID) Controller. This system utilizes the benefits of the Whale Optimization Algorithm (WOA) to increase convergence speed, enhance exploitation and exploration abilities, and accurate speed control by efficiently tuning the parameters of PID to decrease the steady state error and overshoot. The key performance metrics which comprise Rise Time, Settling Time, and Maximum Overshoot are utilized to assess the efficacy of this approach.** Moreover, the presented system is compared with conventional models to showcase the improved effectiveness of the respective model. This innovative approach intends to contribute significantly to studies in areas like robotics, automation, electric vehicles, industrial machinery, and other systems that use BLDC motors for speed regulation.

**INDEX TERMS :** Artificial intelligence (AI), brushless direct current (BLDC) motor, enhanced whale optimization algorithm (EWOA), proportional integral derivative (PID), pulse width modulation (PWM).

## INTRODUCTION

Brushless DC (BLDC) motors [1], [2] are now widely used in mechanical, medical equipment, automotive, aviation, and hard drive applications because of their excellent performance, innovation, and increased driving power efficiency [3]. Currently, experts are exploring the possibility of utilizing Unmanned Aerial Vehicles (UAV) to supervise activities due to their versatility in both military and civilian settings [4]. Operating the UAV system is simple in uninteresting and

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hazardous surroundings in order to safeguard human life. Its key characteristics include its high mobility, ease of organization and maintenance, and user-friendly design. These characteristics provide a helpful alternative for many unregulated military and civilian purposes. The BLDC motors [5], [6] are commonly utilized in UAVs due to their effectiveness, lightweight construction, and strong power-to-weight relationship. Using BLDC motors in UAVs offers benefits such as enhanced fficiency, extended flight durations, and reduced maintenance needs when compared to traditional motors [5], [7]. Importantly, regulating speed is key in BLDC motors [8], [9] as it enables accurate control of the motor's speed, necessary for ensuring stability, efficiency, and performance across different uses [10]. Users can modify the thrust, torque, and overall power output of the motor to meet specific needs by managing the motor's speed [11]. The manual restriction of speed regulation in BLDC motors is due to the intricate and diverse factors that impact motor operation, like load changes, temperature shifts, and voltage fluctuations. Due to its coupled non-linear and multi-input nature, the BLDC motor found more complex problems than its brushed counterpart in terms of control and modelling system design [12]. Conventional manual methods of speed control typically involve operators constantly monitoring and adjusting, which can result in inefficiencies, inaccuracies, and possible performance restrictions. Artificial Intelligence (AI) has transformed speed regulation in BLDC motors [5], [13] by implementing adaptive control algorithms that can automatically modify motor parameters in response to varying conditions. AI-based controllers [14], [15] like adaptive Proportional Integral Derivative (PID) controllers utilize artificial intelligence and predictive modeling to improve motor performance, increase efficiency, and surpass the constraints of manual control [16]. Through the use of AI technology, BLDC motors can attain enhanced speed control, responsiveness, and stability, resulting in increased performance and reliability in UAV applications [17]. Similarly,numerous classic models aimed to achieve improved efficiency in the optimization of speed [2]. For example, the current approach includes a Bidirectional Long Short-term Memory (Bi-LSTM) for speed estimation, with the mean absolute percentage error value measured at 3.25% [18]. The classical approach involves adjusting PID parameters continuously using fuzzy logic-based controls to accommodate plant changes and disturbances, with testing conducted on a BLDC motor, known for its non-linear qualities [19]. Adjust PID settings using fuzzy logic using a set of 49 if-then statements. A two-tiered control system was constructed to adjust PID parameters in real-time. The initial step is to determine PID parameters through the reaction method curve by identifying the minimum and maximum values of kp (Proportionalconstant), ki (Integral constant), and kd (Derivative constant), Experimenting with adjusting set points on BLDC Motor loads under different conditions such as no load and a 0.5-kg load and observing how the PID control system responds with an average rise time of 0.025 seconds, pre-set time of 0.1625 seconds, and overshoot of 15.98%. The average rise time value of the Fuzzy PID control is 0.0025 seconds,with a pre-set time of 0.057 seconds and an overshoot of 5.42% [20]. This study involved creating and simulating the system control of speed for motors of motors with the Fuzzy- PID method. The research is supported using simulation via MATLAB/ Simulink. The simulation utilizes a speed set point input of 650 rpm and employs two approaches: Fuzzy-PID Logic and the conventional Pi method, conducted throughout 1 second. The exam findings indicate that the Fuzzy-PID control outperforms traditional PI control by offering improved and more consistent performance [21]. Similarly, large-scale traditional approaches have been used to improve speed regulation in electric motors, but they are hindered by factors like Rise Time, Settling Time, Maximum Overshoot, and overall efficiency. If the load is varied or increase then it will lead to speed fluctuations in motor, overshoot and oscillations in motor, decrease motor speed, high current consumption and longer settling time. To solve these issues, the proposed model has effectively been handled by optimal current management, robust control, adaptive parameter tuning, faster response to change and improved stability. To attain ideal performance, PID controllers need accurate tuning parameters such as Derivative gains, Proportional and Integral. This process is composite, need substantial capability and time consuming. The traditional models frequently struggle to enhance performance even with AI advancement. Improving the performance and efficacy of BLDC

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motors is significant for many applications containing industrial machinery, robotics and electric vehicles. In this sector, improving speed controlled to crucial improvements. More reliable and consistent performance are attained by optimized, automated control systems. To resolve the issue, the proposed model utilized EWOA-TPID controller intended to attain enhanced efficacy in the BLDC motor speed control. The start of the motor operation involves establishing desired speed and torque values for the motor to reach. These values are put together to form a control signal that manages the torque output of the BLDC motor. Torque estimation techniques are used in feedback control to accurately determine the motor's real torque. The efficiency of the motor is optimized by the WOA. A PID controller observes and regulates the motor's speed and torque output to align with the desired values. The PID controller produces control signals that are transformed into Pulse Width Modulation (PWM) signals to operate a 3-phase voltage source inverter, managing the power provided to the BLDC motor. This procedure guarantees the motor stays at the desired speed and torque levels to achieve optimal performance. The major contribution of the proposed system is signified in the following:

- To employ the EWOA-TPID controller to improve the efficiency and performance of the BLDC motor speed control system.
- To analyze the efficiency of respective research with performance metrics such as Rise Time, Settling Time, and Maximum Overshoot.
- To compare the proposed approach with classical models to reveal the greater performance of the projected system.

This paper is organized based on analyzing conventional research on the control strategy in the electric motor as a literature review in section II. The proposed research methodology is presented in section III. Results and discussion are presented in section IV. Finally, the conclusion is presented in section V.

## II. REVIEW OF LITERATURE

The section analyses the existing research on Speed Control for electric motors. The traditional approach involves the utilization of the Grey Wolf Optimization (GWO) algorithm to effectively adjust the PID controller parameters. This current model aims to analyse the outcomes achieved by adjusting a PID controller using GWO and Particle Swam Optimization (PSO) methods. It has been concluded that the suggested method provides superior dynamic performance for BLDC motor [22]. Research is being performed on the stability and performance of a brushless DC motor in a regular system with a deep-learning neural network -fuzzy-tuned PID speed controller. Additionally, the stability of the conventional controller is examined through the Lyapunov strength criterion by acquiring definite positive functions. The findings indicate that the existing approach resulted in improved effectiveness. Additionally, the conventional method included evaluating the speed control of a BLDC employing a PI controller and a PID controller. It has been discovered that the PID controller outperforms the PI controller in different operating conditions which includes rise time, settling time, and overshoot percentage. The experiment findings show that the PID controller outperforms the PI controller in terms of rise time, settling time, and overshoot percentage. Nonetheless, a slight divergence transpired due to PID. The traditional study examines PID controllers as a more practical choice for effective control performance. This classical research utilized a hybrid approach. PID and PID auto tuner can enhance the system. Adaptability is known as an adaptive PID controller [23], [24]. MATLAB/Simulink simulation platform was utilized to confirm the performance by creating a benchmark system using the real BLDC motor [25], [26] parameters, and auxiliary systems [27]. Correspondingly, the existing method involves utilizing the PID control algorithm to develop the closed-loop speed control of a Brush DC motor. This research aims to create and execute a control system for maintaining the speed of the DC motor despite changes in the load (disturbances), automatically based on the PID controller. The classical system was created and developed using MATLAB/Simulink and a DC motor for execution [28]. In the same way, the traditional approach employs a self-tuning PID controller to regulate a BLDC motor [29] across a broad speed range. The drive's speed performance is evaluated against that of a traditional PID controller. The result of the test reflects improved effectiveness [30]. Likewise, optimization and modelling of the BLDC motor [31] is functioned in the existing method. Here, the firefly algorithm is utilized for the optimization

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mechanism. The results of the prevailing method shows better efficiency in the optimization of the BLDC motor [32].This ground-breaking study improved the whale optimization algorithm to optimize PID controller parameters for efficiently controlling DC motor speed and minimizing settling time. The proposed approach includes high-quality specifications like easy implementation, steady convergence characteristics, and impressive computational efficiency. The simulation of the DC motor's development with fine-tuned PID controller is carried out on the MATLAB/ Simulink platform. A comparison is carried out between the outcomes of the classic model and the algorithm showcases the efficiency of the traditional algorithm [33]. Accordingly, in the existing research, velocity achieved from a Simulink model, which incorporates fluctuating input supply voltages, is utilized as a baseline signal for training and testing a neural controller. Using these reference signals, neural control ensures optimal values for external factors like speed and electromagnetic torque. The outcome of the study allows for the active implementation of the suggested controller utilizing neural network technology. The controller's outcomes are confirmed by comparing them with the theoretical results obtained for the system. MATLAB/Simulink software was used to verify the effectiveness and responsiveness of the controller [34]. Pioneering research employed a hybrid control scheme to regulate the speed of a BLDC motor [35], [36] by regulating both BLDC motor reference current and inverter DC bus voltage simultaneously.A FOPID controller is utilized to regulate the reference current for a BLDC motor, while a fuzzy logic controller is responsible for adjusting the DC bus voltage of the inverter.A revised algorithm based on harmony search (HS) metaheuristic is created to adjust the parameters of a FOPID controller. Three distinct operating conditions are utilized to assess the motor, which includes operating with no load, operating with varying loads, and operating with varying speeds in order to validate the effectiveness of the proposed controller [37]. The classic approach explores enhancing the conventional PID speed controller with a Fuzzy logic component. A BLDC motor [38], [39] simulation model has been developed, along with an inverter, speed detection circuit, and controller. Results from simulations demonstrated that utilizing the Fuzzy-based PID controller can decrease the transient time from 0.2 s to 0.05 s and prevent overshoot when compared to a conventional PID controller. Experimental data demonstrates a noteworthy enhancement in the motor's dynamics, with overshoot and transient time being halved [40].

## III. PROPOSED METHODOLOGY

BLDC motors are effective in mechanical applications due to their strong torque and small design. Using a simple PID controller for peak performance can be challenging. Previous speed control techniques involved adjusting factors like voltage, and current but had limitations. AI integration has been attempted by the existing research, but efficiency improvements are still being worked on. The proposed method aims to address this issue by employing the EWOA-TPID Controller. Figure 1 signifies the overall flow of the proposed system. The described flow methodology consists of several steps in monitoring a BLDC motor system. The process starts by establishing a specified speed and torque for the motor's function. These benchmark values act as goals for the motor to reach while in operation. The following step is to combine the speed and torque references to generate a single control signal.

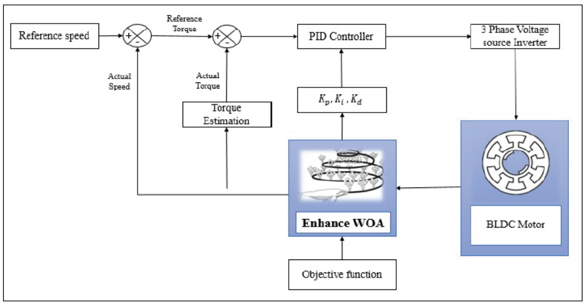


**FIGURE 1.** Diagrammatic flow of the proposed method.

This combined signal is subsequently utilized to regulate the effective torque produced by the BLDC motor. At the same time, methods for estimating torque are utilized to precisely calculate the real torque generated by the motor. This data is essential for controlling feedback and fine-tuning the motor's operation. WOA is working to improve the motor's performance and effectiveness in the control process. A PID controller is used to monitor and adjust the motor's speed in comparison to the reference speed and torque. The PID controller

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aids in adjusting the motor's speed and torque output to align with the target reference values. By adhering to this flow methodology, the BLDC motor system can efficiently uphold the desired speed and torque levels, ultimately resulting in optimal performance and efficiency. The complete depiction of the presented approach is represented in the following sections.

### A. SPEED CONTROL: ENHANCED WHALE OPTIMIZATION ALGORITHM- TUNED PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER

The BLDC motors utilize magnets fixed in a trapezoidal rotor and need a three-phase inverter for functioning. A rotor position sensor is necessary for initiating and ensuring precise rotation by commutating. The process consists of six stages with a 120◦ break between each stage, following a precise sequence of conduction. Adequate operational performance relies heavily on the synchronization and voltage signals, with the current being in the form of rectangular shapes. The motor is controlled by a six-step control system, with its switch and part determining six regulated steps. Converters regulate the current according to the rotor's position, either through position sensors or independently. The electric current flow through both phase windings in BLDC motors that are connected in a star configuration. Here, an unregulated stage is employed to determine voltage concerning counter electromotive force. The equation of the BLDC motor is signified as equation (1), (2), (3) and (4).

$$v_a = Resi_a + L\frac{di_a}{dt} + e_a \quad (1)$$

$$v_b = Resi_b + L\frac{di_b}{dt} + e_b \quad (2)$$

$$v_c = Resi_c + L\frac{di_c}{dt} + e_c \quad (3)$$

$$T_{em} = k_f\omega_m + J\frac{d\omega_m}{dt} + T_L \quad (4)$$

where, the va, vb, vc per phase stator voltages correspond to ia, ib, ic phase currents. The back emf of the stator phases are ea, eb, ec. Stator per phase resistance is denoted by R, while L stands for inductance of the stator winding for each phase. The *kf* denotes voltage constant, the rotor of inertia denoted by *J*. The stator winding per phase self-inductance is signified as L. *Te* is the developed electromagnetic torque. Similarly, the speed of the motor is monitored and then evaluated against the desired speed. The PI controller takes in speed errors and produces the required input voltage for the inverter. The rotor position is identified by hall sensors to produce the switching pulses for the inverter. The effectiveness of regulating speed greatly depends on enhancing the PI controller.
The PI gains of the controller are adjusted in the proposed model using an Enhanced Whale Optimization Algorithm-Tuned Proportional Integral Derivative Controller.Table 1 signifies the parameter values.

| **Motor Specifications** | **Parametric Values** |
|---|---|
| Nominal Speed | 2000 rpm |
| Phase resistance | 2.8750 Ω |
| Phase inductance | 8.5 mH |
| Flux linkage established by magnets | 0.175 Wb |
| Back EMF flat area | 120 Degrees |
| Initial conditions | [ 0,0,0,0] |
| Moment of inertia J | 0.0008 kg-m2/rad |
| Viscous coefficient $K_f$ | 0.001 N-m/(rad/s) |
| Torque constant | 1.4 N-m/A |
| Voltage constant | 0.1466 V/rpm |

**TABLE 1 .** Signifies the parameter values.

Precise regulation of motor speed is crucial in a BLDC motor with a PID controller as it involves controlling the speed effectively. The PID controller adjusts the motor's voltage input based on the comparison between the desired speed set-point and the actual speed feedback.

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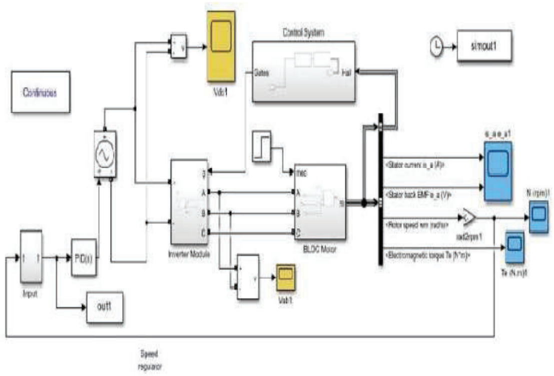


**FIGURE 2.** Architecture of presented model.

Figure 2 illustrates the structure of the model that was introduced. This helps maintain the efficiency and reliability of the BLDC motor in various uses by guaranteeing stable and accurate speed regulation. The system proposed the use of an Enhanced Whale Optimization Algorithm Tuned Proportional Integral Derivative Controller to enhance speed control of the BLDC motor. The proposed research particularly selects ‘EWOA for its good convergence speed, simplicity and balanced optimization capabilities. These advantages improve the parameters of the PID controller in speed control of the BLDC motor. The proposed EWOA-TPID controller integrates the dynamics of the converter which permits for more precise simulation of the complete control loop. This results in more reliable and realistic PID tuning, improving the efficacy and robustness of the system. By allowing these dynamics, the proposed EWOA algorithm can enhance the parameters of PID more efficiently, confirming the compensate of the controller accurately for the influence of converter on the motor, hence obtaining greater performance. The process starts with creating the required parameters for optimizing, such as the number of whales, the size of the search area, and the highest iteration restriction. Then, a starting population of whales is created to kick off the optimization procedure. The whole function is used to verify the fitness criteria and determine if the optimization has converged. The performance of each whale in the population is assessed by evaluating the fitness function for them.An oscillating pattern is created to direct the motion of every whale within the exploration area, assisting in the process of optimization. The optimal solution W and its corresponding fitness value F are discovered for every whale. The proposed Enhanced Whale Optimization Algorithm-Tuned PID (EWOA-TPID) controller generates a control signal designed to optimize the speed and torque of the Brushless DC (BLDC) motor. Unlike traditional PID controllers that directly influence the inverter’s DC link voltage, this controller employs an alternative approach. The control signal from the EWOA-TPID controller interacts with a power converter,

which acts as an intermediary between the controller and the motor. Instead of directly altering the DC link voltage, the power converter processes the control signal and translates it into precise voltage adjustments. These voltage modifications are crucial for maintaining ideal motor performance, ensuring smooth regulation of speed and torque.The power converter plays a critical role in interpreting the actuation signal from the PID controller and converting it into appropriate voltage changes that optimize the motor’s operation. By integrating an AI-based PID controller, which is tuned using the EWOA, the system achieves even greater precision and adaptability. The AI allows real-time tuning of the control parameters, enhancing the efficiency and reliability of the overall control scheme. This advanced model ensures more accurate control, reduces energy losses, and provides a more stable and efficient operating environment for the BLDC motor, resulting in improved performance and extended motor lifespan. The process involved in the proposed speed control mechanism is represented in Figure 3.

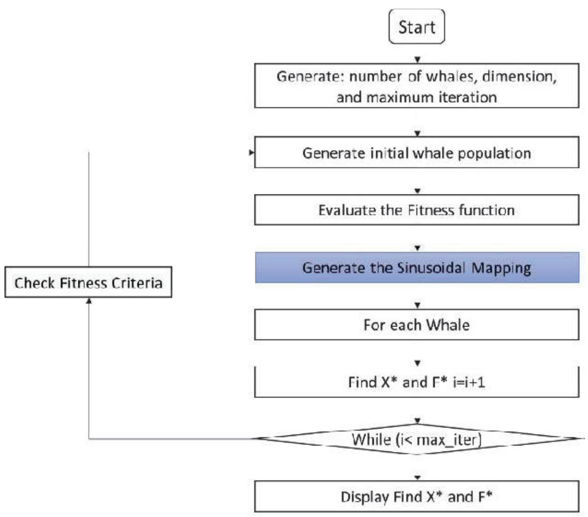


**FIGURE 3 :** Proposed speed control method.

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The iteration counter increases by 1, and the process persists until the iteration count is below the maximum iteration limit. At last, the Enhanced Whale Optimization Algorithm with the Tuned Proportional Integral Derivative Controller, successfully displays the optimal solution W and its fitness value F, demonstrating the efficiency of the optimization procedure. In the proposed EWOA continuous estimation of the gain parameters and the PID is updated accordingly. This thorough method integrates multiple stages to improve optimization effectiveness and efficiently reach the desired outcomes. The mathematical derivation of the proposed system is represented as follows. Equation (5) represents the transfer function of a PID controller.

$$PID = K_p + \frac{K_i}{s} + K_d s \quad (5)$$

where, *Kp* represents relative constant of tuning, *Ki* symbolizes primary adjustment constant, and Kd denotes derived constant of tuning. The act of determining the parameters of PID controller such as *Kp* (proportional gain), *Ki* (integral gain), and *Kd* (derivative gain). The range of *Kp Ki* and *Kd* are shown in the table 2 in order to achieve optimal and reliable performance is referred to as controller tuning. Similarly, traditional WOA is optimization algorithm which is based on bubble net hunting technique of humpback whales and can be applied to various optimization challenges. Equations (6) to (9) represent the formula of the conventional model.

$$W(t+1) = \begin{cases} W^*(t) - AD, & p < 0.5 \\ D'e^{bl}\cos(2\pi t) + W^*(t), & p \geq 0.5 \end{cases} \quad (6)$$

$$D' = |CW^*(t) - W(t)| \quad (7)$$

$$A = 2ar - a \quad (8)$$

$$C = 2r \quad (9)$$

l repre ents an indiscriminate variable within range of [−1, 1], with a being an digit between 2 and 0 that increases linearly with each iteration. r and p are random constants between 0 and 1, while b determines the shape of the spiral motion. t signifies the current iteration, and D represents the distance of i-th whale from optimal solution. If | Z | is greater than 1, the method's convergence is ensured. This involves updating particles in a spiral manner where Humpback whales mimic their spiral-shaped movements while hunting prey, creating a curved relationship between the whale's position and their target. Equations (10) and (11) represent all the search agents. where $V'$ is distance from i-th whale to the prey, l is a random number within range of [−1, 1], t signifies present iteration,$Y$ ,$V$ are the

$$\vec{O_{ji}}(t+1) = \vec{V'}e^{bl} \cdot \cos(2\pi l) + \vec{O_{ji}}^*(t) - \vec{Y} \cdot \vec{V} \quad (10)$$

where,

$$\vec{V'} = \left|\vec{O_{ji}}^*(t) - \vec{O_{ji}}(t)\right| \quad (11)$$

coefficients vectors, *Oji* is the position vector and b is a fixed value that determines the spiral's configuration. The enhancement in the algorithm exploration is achieved through the use of the following equations (12) and (13). The foremost idea supporting the utilization of WOA is that, despite its recent development, it has been applied in diverse scenarios due to its effective exploration capabilities. An issue with the WOA is its inclination to converge early. The system has integrated chaos theory to improve efficiency in terms of convergence. This idea is useful in different areas of science like math and physics. Its basic explanation originates from ancient human understandings of the cosmos. In chaos theory, complicated systems may seem Sinusoidal Mapping, leading them to appear disorderly and unpredictable, despite actually being controlled by a specific mathematical equation. A representation of Sinusoidal Mapping behaviour is shown below in equation (14).

$$D' = |CW_{rand}(t) - W(t)| \quad (12)$$

$$W(t+1) = \begin{cases} W_{rand}(t) - AD, & p < 0.5 \\ D'e^{bl}\cos(2\pi t) + W_{rand}(t), & p \geq 0.5 \end{cases} \quad (13)$$

$$SM_{i+1}^{j} = f\left(SM_i^j\right), j = 1, 2, \ldots, k \quad (14)$$

k denotes the size of the map and $f\ (SM_i{}^j)$ signifies the function that generates the Sinusoidal Mapping model. The parametric values of the proposed model are shown in Table 2. The parametric values of population size is 50, number of iteration is 100. The values vary between 2 and 0 for the parameter of constant and y. The values of Lower bound parameter of Kp, Ki and Kd are 0.001, 0.001 and 0.001. The values of Upper bound parameter of Kp, Ki and Kd are 20, 20 and 20.

| Parametric | alues |
|---|---|
| Size of Populations | 50 |
| Number of iterations | 100 |
| Constant,y | varies between 2 & 0 |
| Lower bound of (Kp,Ki and Kd) | [0.001 ,0.001 , 0.001 ] |
| Upper bound of (Kp,Ki and Kd) | [ 20 , 20 , 20 ] |

**TABLE 2.** Parametric values of proposed model.

The high gain is used to control the aggressive of system and avoid oscillation instability and the low gain is used to stable the system and reduce disturbance through EWOA by tunning approach. This resultant in balance between performance and stability. By implementing Sinusoidal Mapping behaviour, the system convergence and speed can be enhanced, leading to an improved population diversity that helps avoid getting stuck in a local optimum trap. In this section, enhanced WOA is applied using the Singer mechanism. To put this mechanism into action, the unidentified scale factor (γ ) is transformed into a standard calculated value in the following equation (15).

$$X_{Rand,k}^{i+1} = 1.07(7.9 \times X_{Rand,k}^{i} - 23.3 \times (X_{Rand,k}^{i})^2 + 28.7 \times \left(X_{Rand,k}^{i}\right)^3 - 13.3 \times \left(X_{Rand,k}^{i}\right)^4 \quad (15)$$

Correspondingly, the fitness function of the projected method is represented in equation (16).

$$ISE = \int e^2(t)dt \quad (16)$$

Here, $e^2(t)$ signifies the error among actual speed and reference speed. In the simulation used in the suggested study, it is believed that both methods have an equal probability of 50% of being elected, and the search agent then proceeds according to the equations provided in (17) and (18).

$$\vec{O_{ji}}(t+1) = \vec{O_{ji}}^*(t) - \vec{Y} \cdot \vec{V} \; if \, \delta \leq 0.5 \quad (17)$$

$$\vec{O_{ji}}(t+1) = \vec{V'} e^{bl} \cdot \cos(2\pi l) + \vec{O_{ji}}^*(t) - \vec{Y} \cdot \vec{V} \; if \, \delta \geq 0.5 \quad (18)$$

Here,*Oji* signifies the finest solution obtained till now, the position vector is signifies by *Oji*, the coefficient vectors are represent by $Y$ ,$V$ , “ • ” represent the multiplication among elements, δ is a random number in [0, 1] is larger than 1, and the location of the search agent’s exploitation phase is updated by selecting a search agent randomly instead of selecting the best search agent. The search agent follows the equation provided below.

$$\vec{O_{ji}}(t+1) = \vec{O_{ji}}rand - \vec{Y} \cdot \vec{V} \quad (19)$$

$$\vec{V} = \left|\vec{F} \cdot \vec{O_{ji}}rand - \vec{O_{ji}}(t)\right| \quad (20)$$

where, *Oji* and is arbitrary number varies while repetitions are going on. Correspondingly, the efficiency of the proposed approach is evaluated with certain performance metrics.

## IV. ESULTS AND DISCUSSION

The section presents the outcome attained by the presented system.

### A. PERFORMANCE METRICS

The metrics utilized to evaluate the performance of the projected system are signified in this section.

1. **Rise Time:** Duration of a process moving from the starting point to the endpoint. It is the time needed for a system to go from 10% to 90% of its final value in response to a stimulus.
2. **Settling Time:** It is the duration needed for the system’s reaction to reach and remain within a designated range of its ultimate value.
3. **Overshoot:** The maximum overshoot is the highest percentage that the system’s response goes beyond its final value before stabilizing. The evaluation of BLDC motor speed control using a WOA-integrated PID controller depends on important performance metrics to analyse system stability, responsiveness, and overall performance.

### B. PERIMENTAL RESULTS

The section represents the outcome of the proposed model as listed in Table 3.

| S.No | Performance Metrics | Outcomes |
|---|---|---|
| 1. | R e Time | 0.1600 s |
| 2. | Settling Time | 0.1900 s |
| 3. | Overshoot | 0.0001 % |

**TABLE 3:** Outcome of the presented system.

The rise time, at 0.1600 seconds, demonstrates the speed at which the system attains its target velocity following a step input. A quicker rise time is typically preferred as it indicates a swifter reaction, which is efficiently accomplished in this situation. A settling time of 0.1900 seconds indicates the duration for the system to stabilize around the desired speed without oscillations, within a specified tolerance range. A shorter settling time is important for efficient system

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stabilization and smooth operation. An overshoot of 0.0001% signifies that the system stays within the desired speed range without surpassing it, which is a very favourable result. This implies that the system reaches the desired speed without overshooting, guaranteeing stable and precise control. In general, the findings indicate that WOA-Integrated PID Controller Optimization has successfully improved the speed regulation of BLDC Motors, delivering quick response times, steady performance, and accurate control with no overshooting. The parameter of the EWOA-TPID controller is signified in Table 4.

| Parameters | Values |
|---|---|
| Kp | 0.0023745 |
| Ki | 15.301 |
| Kd | 0.005697 |

**TABLE 4.** EWOA-TPID controller parameters.

Optimizing the performance of the PID controller in effectively controlling the speed of BLDC motors relies heavily on these values. The statistical analysis of the proposed system is shown in Table 5.

| Parametric | Values |
|---|---|
| Mean | 4710 , 1035 |
| Rank | 2.5 |
| Standard deviation | 0 |

**TABLE 5.** Statistical analysis of proposed system.

Table 5 shows the statistical values of proposed system for mean, rank and standard deviation of 4710,1035, 2.5 and 0. The following figures represent a comparative analysis based on rotor speed.

## C. COMPARATIVE ANALYSIS

Comparative analysis is carried out to assess the efficacy of the proposed model with other existing models, thus table 6 showcases the comparative analysis performed for a proposed model with prevailing approaches in terms of rise time, settling time and overshoot.

| Designed controllers | Peak Time(s) | Peak Value (rpm) | Peak over shoot (%) | Settling time(s) |
|---|---|---|---|---|
| Fuzzy+PID | 0.9992 | 1516.5 | 0.1651 | 0.6554 |
| AW+Fuzzy +PID | 1.0010 | 1502 | 0.2201 | 0.6669 |
| Existing model | 1.0000 | 1500 | 0.0333 | 0.5863 |
| **Proposed model** | **0.00028** | **2750** | **0.0000** | **0.19** |

**TABLE 6.** Comparative analysis of the presented model with existing method [23].

Table 6 showcases the peak time, peak value (rpm), Peak overshoot (%), and settling time for prevailing designed controllers along with the proposed model. From the table, it has been identified that higher peak time was attained by Anti wind up PID model, a higher peak value is attained by ANFIS+PID, lowest peak overshoot was reached by the existing model. Likewise, Anti-wind (AW) up PID has high steady state error percentage and high setting time been obtained by AW up PID, this outcome proves that proposed work has attained better performance than existing models as lower peak time, peak value, settling time and higher peak overshoot value time demonstrates the ability of the model to achieve stability more rapidly. Further, a low settling time means that the BLDC motor can stabilize the target speed faster with less overshoot. Therefore, when compared to other existing works, the proposed model has delivered a better outcome.

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| Designed controllers | Rise Time (ms) | Overshoot(%) |
|---|---|---|
| PI Controller | 14.58 | 4.737 |
| PID Controller | 12.288 | No overshoot |
| Fuzzy Controller | 11.85 | 0.274 |
| Existing Model | 5.7 | No overshoot |
| Proposed Model | 0.16 | 0.001 |

**TABLE 7.** Comparative analysis of the presented model with the existing method [42].

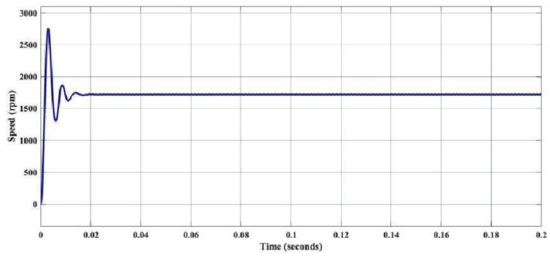


**FIGURE 4.** Comparative analysis of conventional PID controllers based on rotor speed.

From Table 7, it is defined that the proposed model has attained a rise time of 0.16 ms, which is less than 2 ms. Whereas the other controllers indicate the rise time that is greater than 5 ms. Moreover, there is 0.001 percentage, when compared with PI, PID, Fuzzy and existing controller. However, the PI and fuzzy controller attain the overshoot percentage of 4.737 and 0.274. In the figure 5 depicts relatively minor when compared to traditional WOA-tuned PID and PID controllers. Particularly, the proposed model depicts overshoot of almost 5% (0.05) and 3% (0.03) of undershoot. However, the proposed system provides best performance in minimizing undershoot and overshoot. These values are significantly lower than the traditional model. Besides, the existing and proposed model achieves a null percentage of overshoot.

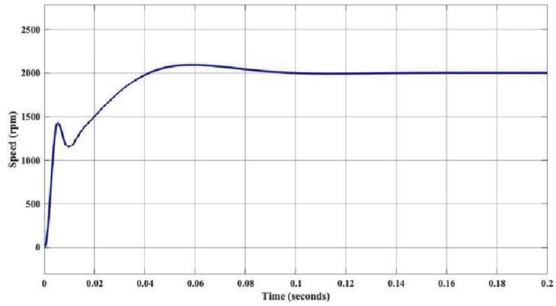


**FIGURE 5**. Comparative analysis of proposed PID controllers based on rotor speed.

Figures 4 and 5 show a comparison of rotor speeds between a conventional PID controller and the proposed PID controller that has been proposed in. The classic controller starting at 2700 rpm, gradually decreases to below 2000 rpm. On the other hand, the PID controller under consideration uses a sophisticated control algorithm to consistently keep the rotor speed at approximately 2000 rpm, demonstrating improved efficiency and stability within the system. The enhanced efficiency is credited to the PID controller's capability to adapt control parameters in response to live feedback, ensuring accurate regulation of the rotor speed and reducing deviations from the desired setpoint. In general, the adaptive control strategy of the PID controller results in operating more efficiently and reliably when compared to the traditional regulator. When compared to exiting model, the proposed model led to reduce settling time, rising time and speedy convergence to the settings of optimal controller due to its efficient and rapid PID parameters tuning. The proposed model is improved by the exploitation and exploration phases this leads to minimal steady-state error and overshoot. Even with differ loads the proposed model permits to retain optimal performance and this resultant in the proposed controller dynamically adjust its loads. This shows that the new system is better at maintaining a constant and preferred rotor speed when compared to the old controller. The chart shows that the Proposed PID controller is more effective than the traditional one in ensuring a stable and consistent rotor speed, indicating its efficacy in managing the system's performance. The superiority of the proposed model in achieving the

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desired rotor speed with greater precision and reliability is evident when comparing the two controllers.

In the context of optimizing the PID controller using the Whale Optimization Algorithm (WOA) for Brushless DC (BLDC) Motors with Enhanced Speed Control, comparison have made for existing model and proposed model, in which the existing approach represents the PID controller without tuning.

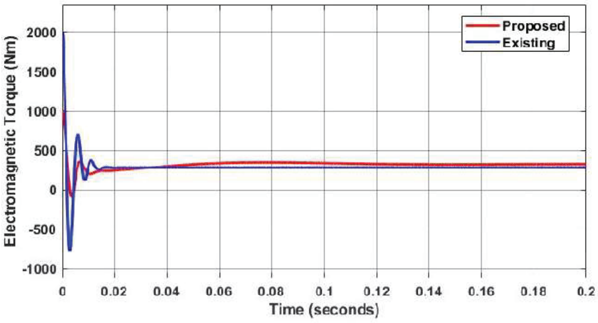


**FIGURE 6.** Transient behavior in electromagnetic -Torque (EMT) in enhanced speed control in BLDC motors.

Figure 6 shows the transient behavior in Electromagnetic -Torque (T) in enhanced Speed Control in BLDC motors, where X axis shows the time from 0 to 0.2 seconds and Y axis shows the torque in Newton-meters. Besides, Blue line denotes the performance of the existing model and red line denotes the performance of the proposed model. Here, the initial transient shows that both system experience oscillations in electromagnetic torque, within the first 0.05 seconds. The oscillations are larger for the existing system, indicating more pronounced overshoot and instability, whereas on the other hand, the proposed system stabilizes faster and exhibits smaller fluctuations, indicating improved control over the torque.

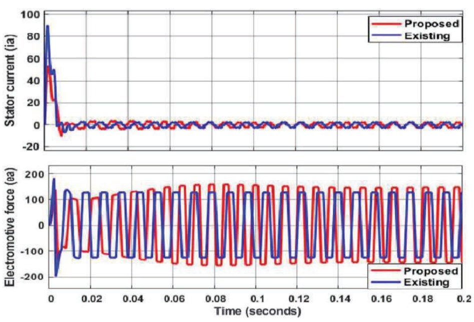


**FIGURE 7.** Transient behavior of stator current and electromotive force in enhanced speed control in BLDC motors.

Likewise, Figure 7 shows the transient behavior of Stator Current and Electromotive force in enhanced Speed Control in BLDC motors, where X axis and Y axis for stator current plot shows represents the stator current in amperes (A) andtime from 0 to 0.2 seconds. Observation of the stator current plot indicates that, proposed system exhibited reduced initial overshoot when compared to the existing model. Similarly, Transient behavior of Electromotive force in enhanced Speed Control in BLDC motors is demonstrated in figure, where X axis represents the Electromotive Force (EMF) in volts and Y axis denotes the time from 0 to 0.2 seconds. The EMF in the proposed model exhibited more consistent oscillation when compared to the existing model, shows the efficacy of the proposed system in the present research work for attaining enhanced efficacy in the BLDC motor speed control.

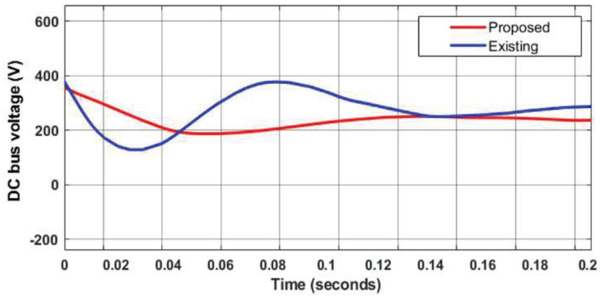


**FIGURE 8.** Transient behavior of voltage in enhanced speed control in BLDC motors.

Figure 8 demonstrates the Transient behavior of Voltage in enhanced Speed Control in BLDC motors, where X axis denotes the time scale in seconds, in which the time scale is approximately from 0 to 0.2 seconds, indicating a short interval where the voltage behavior is being analyzed and Y axis denotes DC voltage in volts. For existing model, there exist a steep drop in voltage initially, going below 200 V and reaching a minimum of nearly 100 V. Then, it recovers, oscillating significantly, peaking at around 500 V and continues to fluctuate before stabilizing near 300 V. whereas on the other hand, in proposed model, more consistent voltage has been maintained and the voltage stabilizes gradually and reaches around 300 V, indicating better control and less fluctuation. Therefore, the proposed system offered better performance in terms of stability and efficiency in controlling DC bus voltage, whereas the existing model has more pronounced voltage swings and instability.

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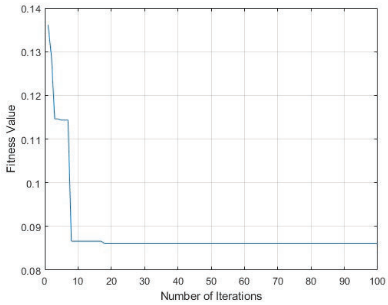


**FIGURE 9.** Performance of proposed system convergence curve.

Thus, the changes in EMT, stator current, and voltage efficiency eventually settle into certain values or ranges over time, demonstrating the desired dynamic balance in the system.The significance of adaptive control strategies like the WOA-Integrated PID Controller Optimization is highlighted by the transient behaviours shown in figures 6-9, showcasing their effectiveness in regulating motor performance under varying operational conditions. Optimisation techniques enable achieving desired motor speeds by adjusting control parameters in response to changing EMT, stator current, and voltage, ensuring stability and efficiency. When compared to the existing model [43], the approached research reaches to 2500 rpm in overshoot and undershoot and then it will stable. In the proposed model the controller reaches 1400 rpm, and it will shuttle in 2000 rpm. When compared to traditional PID and WOA, the proposed EWOA-tuned PID controller is shorter. Particularly, the traditional model achieves 1.2 seconds of raising time and the proposed system attains 0.8 seconds. The settling time of the traditional model is 2.5 seconds, but the proposed model attains a lower settling time of 1.5 seconds. This shows that the proposed model alleviates the system more effectively for faster attainment. Another important metric is over-boost, the traditional model achieved 15% whereas the proposed model attained only 5 %. This indicates the proposed system significantly reducing the risk of potential damage and system instability. Therefore, the illustrated momentary changes in behaviour are a useful benchmark for boosting the overall effectiveness of BLDC motor systems in practical situations.

## V. CONCLUSION

In conclusion, Brushless DC motors are commonly used in mechanical applications because of their efficiency, torque, and compact size. However, improving performance with a customized PID controller can pose challenges. Traditional methods of speed control need to manually adjust voltage, and current, leading to inefficiencies. Attempts to improve speed control with artificial intelligence have fallen short of expectations. The objective of the EWOA-TPID Controller is to address these issues and enhance speed control efficiency. The effectiveness of the method is evaluated using important performance measurements like rise time, settling time, and overshoot. The proposed model’s results indicate a Rise Time of 0.1600 seconds, showing a fast response. A Settling Time of 0.1900 seconds allows for stable functioning without any oscillations. There is 0.001% of overshoot, guaranteeing accurate control within specified boundaries. Moreover, the traditional controller can achieve speeds of 2700 before stabilizing and decreasing to under 2000. However, the suggested model sustains a velocity of approximately 2000, showing that it is better at regulating the rotor’s speed. This indicates that the suggested system is better at keeping a steady and desired rotor speed than the standard controller. In general, the optimization of the PID controller combined with WOA improves the speed regulation of BLDC motors significantly. In the same way, the results of the comparison show that the proposed model is more effective.

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