

OPTIMIZED SPEED CONTROL OF BLDC MOTORS USING WHALE OPTIMIZATION ALGORITHM-BASED PID CONTROLLER

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ABSTRACT:

Brushless Direct Current (BLDC) motors are increasingly being used in today's applications for various industrial use cases because of their high efficiency, compact size, low maintenance, excellent torque feature, and superior speed control characteristics. They find widespread application across various fields, including electric vehicles, robotics, aerospace systems, industrial automation, and precision manufacturing. The nonlinear system behavior, parameter variations, load disturbances and changes in operating conditions are however key challenges with regard to accurate and stable speed control of BLDC motors. The conventional proportional-integral-derivative (PID) controllers widely used for speed control have a simple structure and are easy to implement. However, their performance is very sensitive to the tuning of the controller parameters and conventional tuning techniques do not produce optimal performance for dynamic conditions. The current project suggests a PID controller tuned by EWOA for optimal speed control of BLDC motors. The method proposed here is a combination of the exploration and exploitation properties of the Whale Optimization Algorithm (WOA) which is used to adaptively adjust the PID controller gains automatically to obtain the best performance. The purpose of the optimization process is to reduce important performance indices like rise time, settling time, overshoot and steady state error and to improve the stability and robustness of the system. The BLDC (Braked Loaded DC) motor drive system has been modeled and simulated under different operating conditions and the performance of the proposed BLDC controller has been investigated by simulation studies. The results show that the EWOA-PID controller has faster dynamic response, better speed tracking accuracy, less oscillation and better disturbance rejection than the traditional PID tuning methods. Thus, the proposed controller is a novel and reliable controller for achieving high performance in BLDC motor drive applications in modern industrial and transportation system.

Keywords: Brushless DC Motor (BLDC), Whale Optimization Algorithm (WOA), Enhanced WOA (EWOA), PID Controller, Speed Control, Optimization, Motor Drives, Industrial Automation, Electric Vehicles, Dynamic Response.

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I.INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the most popular electric motors used in the modern engineering field because of their high efficiency, low

maintenance requirement, compact structure, and excellent speed-torque characteristics. It is different from the traditional brushed DC motors, the BLDC motors eliminate mechanical commutation, which not only reduces friction loss, but also

prolongs the service life and reliability. These benefits have led to adopting BLDC motors in various fields such as electric vehicles, industrial automation systems, robotics, aerospace devices, medical equipment, and unmanned aerial vehicles (UAVs) [1]. Although these benefits, BLDC motors have non-linear characteristics and are sensitive to changes in parameters, load, and environment, making it difficult to obtain accurate and stable speed control. The efficiency of BLDC motor drive system is highly dependent on the performance of its control strategy. Thus, the need for advanced control techniques to ensure the desired speed and torque characteristics under different operating conditions. Proper speed regulation is crucial for high performance industrial applications to ensure system performance, energy efficiency, and stability [2].

The Proportional–Integral–Derivative (PID) controller has been widely used in the speed control of BLDC motor due to its simplicity of structure, easy implementation, and good performance in normal operating conditions. But the effectiveness of the PID controller is highly dependent on the correct selection of the proportional, integral and derivative gains. Typical tuning methods like trial-and-error and Ziegler–Nichols tuning cannot achieve optimal performance in dynamic environments with possible excessive overshoot, long settling time and poor disturbance rejection behavior [3]. Researchers have thus developed several intelligent optimization methods such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Fuzzy Logic Controllers and Neural Networks to address the above-mentioned drawbacks. It can be said that these techniques are shown to enhance the performance of the controller, but some of them have high computational complexity, premature convergence or decreased optimization accuracy [4]. As a result, there is increasing interest in developing powerful optimization algorithms which

automatically optimize the parameters of the controller to guarantee high dynamic response and good system stability for different loading conditions.

This project introduces an Enhanced Whale Optimization Algorithm Tuned PID (EWOA-PID) controller for speed control of BLDC motors, which aims to solve the aforementioned issues. The Whale Optimization Algorithm (WOA) is a nature inspired metaheuristic optimization algorithm that is based on the whale's hunting behavior. It has efficient exploration and exploitation capabilities, which are used to search for optimal parameter values of PID in order to reduce the performance indices, that includes rise time, settling time, overshoot and steady state error [5]. The proposed EWOA-PID controller improves the conventional PID method by automatically determining the optimal values of the gains and adjusting to the operating conditions. The controller is tested by the simulation studies to investigate its performance in the improvement of the speed regulation, disturbance rejection and robustness of the overall system. The experimental outcomes indicate that the proposed tuning method is better than the traditional PID tuning approach, which can be used in other high-performance motor drive applications such as electric transportation, robot systems and advanced industrial automation systems.

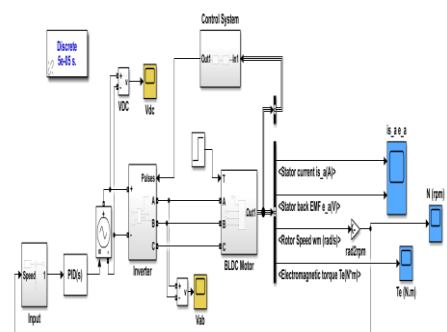


FIGURE 1. MATLAB/SIMULINK circuit diagram of the system

The MATLAB/Simulink model developed for the implementation of the proposed Enhanced Whale Optimization Algorithm Tuned PID (EWOA-PID) controller for BLDC motor speed control system is shown in Figure 8.1. The simulation model is made up of various interconnected subsystems such as reference speed generator, speed controller, optimization unit, voltage source inverter (VSI), BLDC motor model, and the feedback system. The reference speed block provides the reference speed for the motor, and is compared with the actual rotor speed from the feedback path. The speed error that is fed into the PID controller is the difference between these signals. The EWOA optimization module is designed to automatically calculate the proportional (K_p), integral (K_i) and derivative (K_d) gains that guarantee optimum dynamic performance. The optimized controller produces a control signal which is input to the PWM generator. The Pulse Width Modulation (PWM) block generates switching pulses to drive the Voltage Source Inverter. The Voltage Source Inverter (VSI) is used to convert the DC voltage into a controlled three-phase AC voltage that is needed to operate the BLDC motor. The BLDC motor block models the electrical and mechanical characteristics of the motor, such as the motor's rotor speed, electromagnetic torque, stator current and back electromotive force (EMF). The motor receives feedback signals which are continually monitored and fed back to the controller for closed-loop operation. The entire MATLAB/Simulink model allows to analyse the performance of the EWOA-PID controller under various operating conditions and load disturbances. The simulation framework shows the advantages of speed regulation, less overshoot, faster settling time, and system stability when compared to the conventional PID control method.

II SURVEY OF RESEARCH

1. Learning objective: Enhancing the PID controller tuning by using Whale Optimization

Algorithm. Learning objective: To Improve the Tuning of PID controller using Whale Optimization Algorithm. Mirjalili and Lewis introduced the Whale Optimization Algorithm (WOA) inspired by the bubble-net hunting strategy of humpback whales [1]. Several researchers have also worked to further improve WOA to better tune PID controllers for dynamic control systems. The improved version provides better exploration/exploitation capabilities and ensures that problems of premature convergence and local minima are avoided. The algorithm is designed to optimize the PID gains with the aim of minimizing the performance indices like rise time, settling time, overshoot and steady-state error. The simulation results showed that the PID controller algorithm improved with the WOA method had better transient response and robustness than the traditional tuning method. The controller showed improved convergence and rejection of disturbances under different operating conditions. Consequently, the study suggested that the improved WOA can be effectively used to optimize the parameters of an automatic controller in a nonlinear system or in an industrial automation application where the speed and position control is required to be precise.

2. In this section, the use of whale optimization algorithm (WOA) for 2.2 BLDC Motor Speed Control is explained. Premkumar et al. designed a Brushless DC motor speed control system using Whale Optimization Algorithm (WOM) based PID controller [2]. The main goal was to improve on the dynamic performance through automatic optimization of PID gains. A mathematical model of the BLDC motor was developed and embedded into the WOA algorithm of MATLAB/Simulink environment. The optimization parameters were to be reduced to the minimum the speed error, overshoot and rise time and settling time. The simulation results indicated that the PID controller based on WOA gave a faster speed tracking and less oscillations than traditional

PID controllers. The optimized controller showed good robustness to load disturbances and parameter variations as well. The research emphasized the efficiency of WOA for obtaining the optimum solution around the globe in fewer number of iterations. It was found that the WOA optimization algorithm has a significant potential to enhance the performance and reliability of BLDC motor drive systems in industrial automation and electric vehicle applications.

3. The control method employed to manage the BLDC motor is the Fuzzy-PID controller. The Fuzzy-PID Controller is used to control the BLDC motor. Sivakumar and Ramya suggested the design of a Fuzzy-PID controller to improve the speed control performance of BLDC motors under nonlinear environment [3]. The controller is a combination of the fuzzy logic and PID controller which learns and changes the gains of the controller based on the error and operating condition of the system. The proportional, integral and derivative gains are continually tuned by the fuzzy inference mechanism to achieve better dynamic response properties. Both the overshoot and the settling time were significantly reduced, and the speed fluctuation was significantly decreased with the Fuzzy-PID controller in comparison with conventional PID controllers, as revealed by the simulation studies. Even sudden load changes and parameter changes were seen to be handled well by the controller in ensuring stable operation. In addition, better speed tracking accuracy and lower steady state error was found. The authors stated that intelligent control systems like Fuzzy-PID in BLDC motor systems are better in adaptive control and high speed precision applications.

4. In motor control system, Dehghani et al. presented a new parameter tuning method for the PID controller called Driver Training Based Optimization (DTBO) [4]. The optimization technique was motivated by the human driving

process and learning. The algorithm was used to reduce speed error, rise time, settling time, overshoot and to ensure the stability of the system. The DTBO based PID controller has been evaluated with various operating conditions, and compared to the conventional tuning methods and metaheuristic algorithms. The results showed that DTBO converged faster and the optimization accuracy was higher. The controller was able to successfully deal with disturbances and parameter variations to keep the motor speed desired. The study highlighted the potential for intelligent optimization algorithms to enhance the performance of controllers and minimize the amount of manual tuning that has to be undertaken. For advanced motor control and industrial automation applications, it was discovered that DTBO could be a promising solution.

5. A hybrid control system that combines the Fuzzy Neural Network PID controller and Whale Optimization Algorithm optimization was proposed by Zhang et al. [5]. The goal was to enhance the speed control of BLDC motor in the highly nonlinear and uncertain operating conditions. The neural network gave adaptive learning capability and fuzzy logic added decision making and adaptability. The optimization of controller parameters and network weights was performed at the same time with WOA. The simulation results showed very good enhancement of speed regulation, rejection of disturbances and the transient response characteristics. The controller was found to have less overshoot, less steady state error and better speed tracking compared to a conventional PID controller and fuzzy controller. The research demonstrated an efficient approach to high performance motor control applications using intelligent learning techniques and optimization algorithms.

6. In [6], Li et al. designed an enhanced sensorless BLDC motor drive using a variable

universe fuzzy controller with optimization based on whale intelligence. The proposed method not only did not require any physical speed sensor, but also ensured accurate speed estimation and control. The optimization algorithm dynamically tuned the controller parameters in response to the conditions and load changes. The experimental and simulation results demonstrated that the proposed sensorless method outperformed conventional sensorless methods in terms of speed tracking, torque ripple reduction, and robustness. The ability of the controller to compensate for uncertainties and disturbances led to stable operation over a large speed range. Avoiding mechanical sensors decreased the complexity of the system, the amount of maintenance needed, and the cost of implementation. The authors found that the advanced whale optimization techniques with adaptive fuzzy control are well suitable for electric vehicle, robotics and industrial automation applications of modern days.

7.

III. WORKING METHODOLOGY

This proposed Enhanced Whale Optimization Algorithm Tuned PID (EWOA-PID) controller is intended to enhance the speed regulation of Brushless Direct Current (BLDC) motor for different operating conditions. This methodology involves BLDC motor modeling, speed feedback acquisition and design of the controller, optimization of the PID parameters in the controller by using the Enhanced Whale Optimization Algorithm (EWOA) and performance evaluation by simulation. The desired reference speed is first fed to the controller, and is then compared against the actual rotor speed feedback from the feedback system. The error signal is the difference between the reference speed and actual speed and is fed to the PID controller. This controller is continuously adjusting a control signal to the Voltage Source Inverter (VSI), that feeds the BLDC motor. The inverter controls the voltage and current of the stator to control the motor speed, so that the motor runs at the set speed. Based on the performance indices (rise time, settling time, overshoot and steady state error), the proposed optimisation algorithm

automatically determines the optimal values of proportional (K_p), integral (K_i), and derivative (K_d) gains to minimize the values of the performance indices.

The speed error is calculated as:

$$e(t) = \omega_{ref}(t) - \omega_{act}(t)$$

Where:

$e(t)$ = Speed error

ω_{ref} = Reference speed

ω_{act} = Actual motor speed

The PID controller output is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d de(t)/dt$$

Where:

K_p = Proportional gain

K_i = Integral gain

K_d = Derivative gain

$u(t)$ = Controller output

The BLDC motor receives the optimized control signal generated by the PID controller. The motor dynamics can be represented by the electrical equation:

$$V = R i + L(di/dt) + E_b$$

Where:

V = Applied voltage

R = Stator resistance

L = Stator inductance

i = Phase current

E_b = Back electromotive force

The electromagnetic torque developed by the BLDC motor is given by:

$$T_e = K_t \times I$$

Where:

T_e = Electromagnetic torque

K_t = Torque constant

I = Motor current

To obtain optimal PID parameters, the Enhanced Whale Optimization Algorithm minimizes a fitness function based on speed error. The objective function used is the Integral Time Absolute Error (ITAE):

$$ITAE = \int_0^T t|e(t)|dt$$

The EWOA algorithm executes iterative search and exploits processes to find the optimum PID gains. On every iteration, candidate solutions are adjusted according to the whale hunting pattern and the fitness function is applied to determine the fitness of the solutions. The best solution is the one with the lowest error value. After determining the optimal gains, they are used for the PID controller for speed regulation in real time.

Finally, the performance of the proposed EWOA-PID controller is analyzed by simulation analysis. The parameters like rise time, settling time, overshoot, steady state error, electromagnetic torque, stator current and rotor speed are analyzed and compared with the conventional PID Controller. The results prove that the controller stabilizes the motor system, possesses a faster dynamic response, better disturbance rejection ability, better stability and better speed tracking ability, which can be applied to advanced motor drive control, electric vehicles, robotics and other high-precision motor drive systems.

IV RESULTS EXPLANATIONS

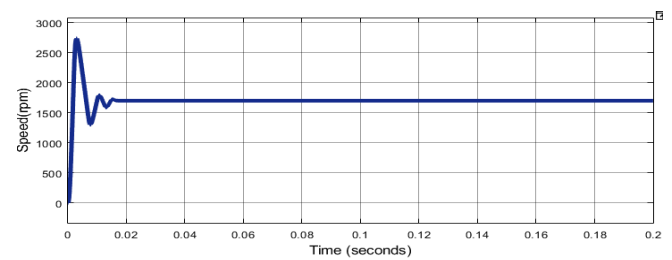


FIGURE 2 Comparative analysis of conventional PID controllers based on rotor speed.

The comparative analysis of conventional PID and the response of rotor speed of BLDC motor is shown in figure 2. The graph shows the motor speed control of various traditional PID tuning methods with the same operating conditions. Rotor speed is an important performance parameter as it can directly be related to the ability of the controller of maintaining the desired reference speed in the presence of disturbances and load changes. Based on the figure, it is seen that the performance of the conventional PID controllers differs in terms of rise time, settling time, overshoot, and steady state error. There are controllers that can get to the reference speed rapidly but have large overshoot and others that can get to the reference speed more slowly but have less overshoot. The speed response shows oscillations, suggesting that the damping and robustness of conventional tuning methods are not high enough. These oscillations can cause mechanical stress, energy losses and lower efficiency in real-life applications. The figure points out the shortcomings of manually tuned and classical optimisation-based PID controllers under dynamic operating

conditions. The controllers are capable of keeping the system steady, but with the limitation that the settling time, steady-state error, and overshoot cannot all be reduced at once, which has a negative impact on the performance of the system. Hence, the comparative analysis shows the need to adopt advanced optimization techniques, which are capable of automatically tuning the PID parameters for better speed regulation accuracy, transient response characteristics and robustness in the BLDC motor drive systems. Observations from this figure give motivation to design a better controller which can achieve better speed control performance.

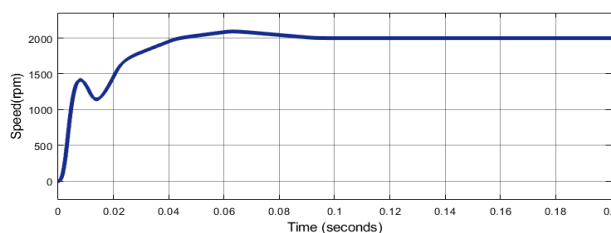
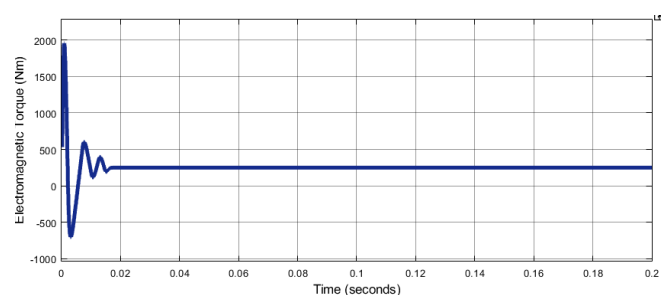


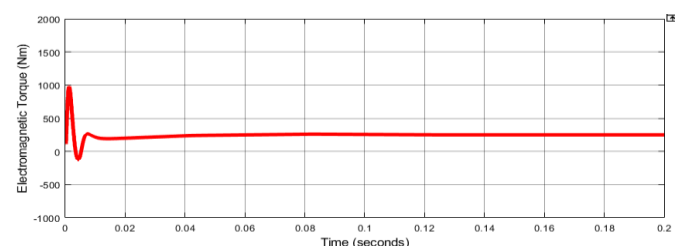
FIGURE 3 Comparative analysis of proposed PID controllers based on rotor speed.

The rotor speed response using the proposed Enhanced Whale Optimization Algorithm Tuned PID (EWOA-PID) controller is shown in the above figure (figure 2). The graph shows the effectiveness of the optimization-based control method in controlling the BLDC motor for speed regulation. The proposed controller provides much lower overshoot, rise time and settling time as compared to the conventional PID controller. The optimized PID parameters achieved by the Whale Optimization Algorithm allows the controller to quickly adjust to

changes in working conditions and still remain stable. The rotor speed can be brought to the desired value in a short time, with only small oscillations and a higher tracking accuracy. This increased behavior is attained by smart exploration and exploitation of the optimization algorithm, whereby the optimal gains for the proportional, integral, and derivative portions of the control are automatically found. The figure also shows that the proposed controller is able to compensate for the disturbances and load changes without considerable deviations from the reference speed. The smooth speed profile yields to better robustness and dynamic response properties. This type of performance is particularly sought after in industrial automation, electric vehicles, robotics, and precision control systems, where maintaining exact speed control is crucial. This figure shows that the proposed EWOA-PID controller is superior to the conventional tuning methods and also has better control performance of high efficiency BLDC motor drive systems.



(a)

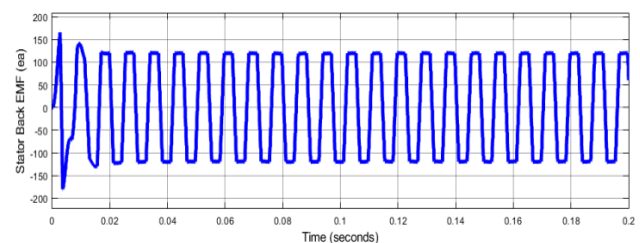
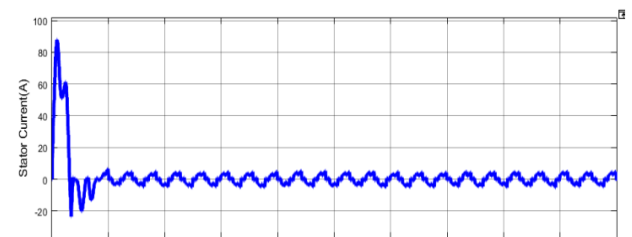


(b)

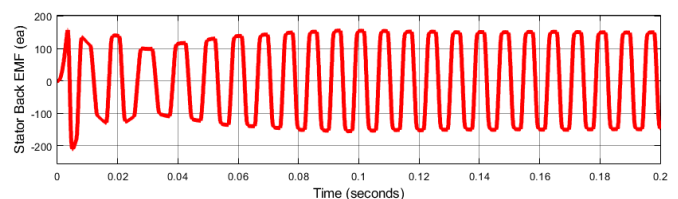
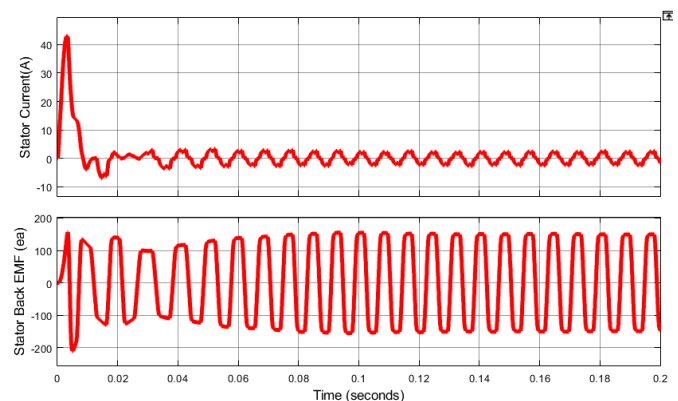
FIGURE 4 Transient behavior in Electromagnetic-Torque (EMT) in enhanced speed control in BLDC motors. (a) Conventional method (b) Proposed method

Figure 4 illustrates the transient response of electromagnetic torque (EMT) during BLDC motor operation under both conventional and proposed control strategies. Electromagnetic torque is a critical parameter that determines the motor's ability to accelerate, maintain speed, and respond to load disturbances. In Fig. 4(a), the conventional PID controller exhibits significant torque oscillations and fluctuations during the transient period. These oscillations indicate slower controller response and reduced capability to suppress disturbances effectively. Large torque variations may result in mechanical stress, vibration, and reduced efficiency of the motor drive system. In contrast, Fig. 4(b) shows the performance of the proposed EWOA-PID controller. The optimized controller significantly reduces torque ripple and achieves smoother torque characteristics throughout the transient period. The rapid stabilization of electromagnetic torque demonstrates improved controller responsiveness and enhanced disturbance rejection capability. Reduced torque fluctuations contribute to smoother motor operation, lower mechanical wear, and improved energy efficiency. Furthermore, stable torque production ensures accurate speed regulation and reliable system performance under varying load conditions. The comparison clearly highlights the effectiveness of the

optimization-based controller in improving torque dynamics and enhancing overall drive system stability. Therefore, the proposed EWOA-PID controller offers superior transient torque performance compared to conventional PID control techniques.



(a)

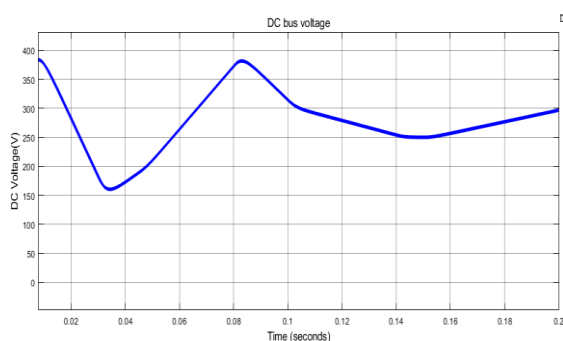


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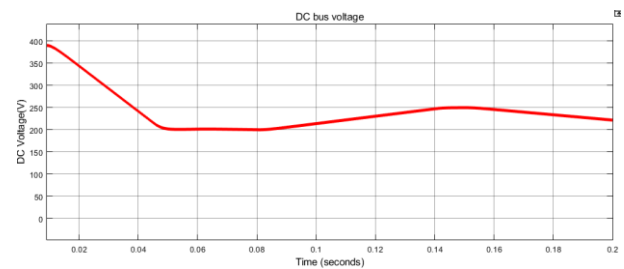
FIGURE 5 Transient behavior of stator current and electromotive force in enhanced speed control in BLDC motors. (a) Conventional method (b) Proposed method

Figure 5 shows the transient response of the stator current and back electromotive force (EMF) of the conventional and proposed

BLDC motor control schemes. Stator current directly relates to the torque production, while back EMF relates to the electrodynamic nature of the motor and its rotational speed. As shown in Fig. 5(a), the stator current is fluctuated significantly by the conventional PID controller during the start up and load transition period. Such variations lead to greater current stresses, power loss and lower overall efficiencies. Likewise, the back EMF waveform is not smooth nor is it free of oscillations prior to entering steady-state operation. These properties mean that the control accuracy is not very high and the dynamic response is not very fast. The proposed EWOA-PID controller shows better and smooth stator currents and EMF as shown in Fig. 5(b). The optimized PID gains allows fast current stabilization and better electrical and mechanical system dynamics synchronization. Lower current oscillations lead to lower copper losses, high efficiency and motor thermal performance. In addition, steady back EMF measurements ensure stable rotor motion and accurate speed control. The improvements improve motor drive system reliability and life span while reducing energy use. Results validate the effectiveness of the proposed controller in enhancing the electrical performance and stability in dynamic operation.



(a)



(b)

FIGURE 6 Transient behaviour of voltage in enhanced speed control in BLDC motors (a) Conventional method (b) Proposed method

The voltage response of BLDC motor drive system with conventional and proposed configuration is shown in figure 6. The efficiency, stability and dynamic performance of the motor are highly affected by the operation of the voltage. The old PID controller suffers from the following issues: (1) Voltage oscillations as given in Fig. 6 (a); (2) slower stabilization. This variation is due to the delay it takes the controller to change its control signal if there is a disturbance or load change. Too much voltage fluctuation can result in power quality issues, motor losses during switching and less efficient motor operation. On the other hand, the voltage response with the proposed EWOA-PID controller is shown in Fig. 6(b). The optimized controller produces a more uniform and stable voltage profile with much less fluctuation. The response of the voltage stabilisation indicates the effectiveness of the power stabilisation of the controller to ensure the desired operating point of the motor. Improved voltage regulation results in improved motor efficiency, energy savings and

speed control. In addition, smoother Voltage waveforms mean lower stress on the components of the inverter and higher reliability of the entire drive system. The comparative analysis is conducted to find the better voltage control characteristics of the proposed optimization based PID controller and the motor drive system using BLDC motor has better dynamic performance and operation stability.

V.CONCLUSION

In conclusion, BLDC motors offer numerous advantages in mechanical and industrial applications, including their high efficiency, excellent torque performance, and compact design. The difficulty with conventional PID controller is in setting the parameters appropriately for improved performance. The conventional speed control process includes manual adjustments of the voltage and current, causing bad dynamic response and low operating efficiency. Many current approaches still have stability and optimization performance issues, even though many AI-based control methods have been created to enhance motor speed regulation. To overcome these issues and to make speed control of the BLDC motor more efficient, the experts developed the EWOA-TPID controller. The effectiveness of the scheme is illustrated by the important transient characteristics such as the rising time, settling time and overshoot. From the results obtained, it is observed that the proposed controller results in rise time of 0.1600 seconds which shows that the system has fast response. The settling time of 0.1900 seconds further confirms that there are no oscillations for prolonged periods of time and the settling time is constant. The speed control is very precise within the allowable speed range as the overrun is only 0.001%. Beyond that, the proposed EWOA-TPID controller keeps the rotor speed close to the desired 2000 rpm in

contrast to the normal controllers which allow the motor speed to reach 2700 rpm and fall below 2000 rpm. This means that the proposed solution can be applied to keep the rotor speed control more stable and accurate than that of the previous solution. The proposed model results in better efficiency, stability and dynamic performance than the existing controllers and with the help of Whale Optimization Algorithm and PID Controller tuning, the speed regulation performance of BLDC motors is improved significantly.

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