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Enhancing Torque Smoothness in BLDC Motors with Built-in DC-DC Converter via Bitterling Fish Optimization Algorithm

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Abstract

Brushless DC (BLDC) motors are efficient and robust electric motors with fewer moving parts, but their application is often limited by torque ripple, which arises from current variations between the entering and exiting phases during commutation. This study aims to minimize torque ripple in BLDC motors integrated with a DC-DC converter. The proposed optimization method utilizes the Bitterling Fish Optimization (BFO) Algorithm to effectively control torque error and speed, addressing the torque ripple caused by current variations during commutation. The proposed method is implemented using the MATLAB working environment and compared with various existing methods like Spider Web Algorithm (SWA), Improved Tunicate Swarm Optimization Algorithm (ITSA), and Harris Hawks Optimizer with Black Widow Optimization (HHO-BWO). The results indicate that the proposed method achieves a reduced torque ripple rate of 9.64, significantly lower than the rates of 17.32, 11.20 and 22.19 for ITSA, HHO-BWO and SWA respectively. Additionally, the proposed approach exhibits low error of 0.168, outperforming the existing methods errors of 0.287, 0.195 and 0.311. These findings demonstrate that the BFO algorithm effectively minimizes torque ripple more than existing optimization techniques, providing a promising solution for enhancing the performance of BLDC motors.

Keywords: BLDC Motors, Bitterling Fish Optimization, Commutation, Diode Bridge Rectifier, Speed Control, Switched Inductor, Torque Ripple

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1. Introduction

a) Background

In general, timings in the future and current are uncertain, despite the high capacity of the DC to DC converter depending on speed driving structures [1]. The BLDC motor, which is used in home machines, automotive equipment, and aeronautics, is thought to be the finest choice for these qualities because of its small size, simple control high power density, and easy operation. Two classes make up BLDC motors [2, 3]. These are BLDC motors with permanent magnets that are mounted both inside and outside. BLDC motors, sometimes referred to as permanent magnet synchronous motors, are commonly employed as servo system drives [4-6].A rotor consisting of BLDC motors and a static armature uses an electronic control commutation method to distribute the electric power instead of a mechanical commutator that uses brushes. Unlike BLDC motors, which use a mechanical commutator, BLDCs electronically accomplish commutation by incorporating input into a control system in the form of rotor position [7-9]. Sinusoidal current waveforms are supplied by regular BLDC motor drivers, which promote smooth motor operation [12, 13]. Torque ripple may result from a sinusoidal commutation if there isn't a dysfunctional sinusoidal distributed magneto-motive force [10, 11].

b) Literature Review

Many research papers focusing on BLDC motor torque ripple mitigation have already been published in the literature. Here is a description of a few of the works.

Hybrid Control Techniques for Torque Ripple Mitigation:

Kommula and Kota [14] presented an integrated converter design that uses the ITSA technique to minimize torque ripple in BLDC motors. The work suggested a hybrid control strategy and better DC-DC converter architecture to lessen torque ripple in BLDC motors. Here, the Cuk converter performs better and works better thanks to the usage of a switched inductor. The performance of the control loop was enhanced by applying the Optimizing Tunicate Swarm technique. The suggested work investigates the ITSA algorithm for BLDC motor speed and torque error control.

Bharanigha and Shuaib [15] have demonstrated how to minimize torque ripples using an improved controller for BLDC motor four-quadrant operation and control. The multifunctional APID controller suggested in this study will control the BLDC motor's speed. To reduce torque ripples and use the APID controller to manage the BLDC motor's speed, the best benefit parameters must be chosen. The suggested method was kindly designed to minimize the problems with scientific figures and has a simple structure. To identify the issue in the work, the optimization techniques that were motivated by the characteristics of HHO and BWO were first solved. The suggested method creates a cohesive plan for the successful methodology.

Optimization Algorithms for Torque Ripple Reduction:

Prakash and Naveen [16] presented a hybrid GEO-RBFNN approach for tuning sensor-less BLDC motors, focusing on reducing torque ripple and improving speed and torque control. The method combines the Golden Eagle Optimization algorithm and Radial Basis Function Neural Network to optimize the factors of a PID controller, enhancing its performance. Additionally, they introduced a modified bridgeless Single-Ended Primary-Inductor Converter to further improve motor control.

Rajesh and Saravanan [17] presented an improved Jellyfish Search (ImpJS) algorithm to minimize torque ripple in a Cuk converter-based BLDC motor. The study involved the integration of a switched inductor into the Cuk converter to enhance the BLDC motor's performance, particularly in speed and torque control. The suggested ImpJS algorithm was utilized to fine-tune the gain parameters of the controller, optimizing its operation for torque ripple minimization and improved motor efficiency.

Anshory et al. [18] suggested a technique that uses the Firefly algorithm and a PID controller to optimize the performance of a DC-DC Boost Converter circuit that drives a BLDC motor. The study included simulation testing to assess improvements in transient response after mathematical modeling of the circuit in the form of transfer functions. The integration of the Firefly algorithm in optimizing the PID controller notably improved system efficiency by ensuring faster stability, reduced oscillations, and quicker settling time, thereby enhancing the overall dynamic response of the DC-DC converter.

Naqvi et al. [19] presented a thorough method for optimizing BLDC motor speed control, energy consumption, and efficiency by using particle swarm optimization and restricted Differential Evolution to tune PID controllers. Their methodology demonstrated significant improvements in motor speed control and overall energy efficiency, underscoring the potential for optimizing BLDC motors in EV applications.

Sensorless and Sensored Designs for Torque Ripple Reduction:

Fathima and Vijayasree [20] have shown how to reduce torque ripple in both sensored and sensorless BLDC motor designs by using a spider-based controller. The suggested work provides a simple torque ripple reduction controller for both sensorless and sensored BLDC motors, based on a bio-inspired spider web algorithm. A switching capacitor, a spider web-based controller, and a hybrid filter are all part of the torque ripple reduction circuit. The spider web controller produces switching signals to regulate the voltages of the capacitors and inverter switches. Table 1 Show that Key findings from the literature

Table 1. Key findings from the literature

Authors	Methodology	Key Findings
Kommula and Kota [14]	Enhanced Cuk converter with ITSA algorithmfor BLDC motor torque ripple reduction	ITSA improved BLDC performance by optimizing speed and torque control
Bharanigha and Shuaib [15]	APID controller with hybrid HHO-BWO optimization for BLDC torque ripple reduction	Effectively reduced torque ripple and regulated speed
Prakash and Naveen [16]	SEPIC converter with GEO-RBFNN for sensorless BLDC motor	GEO-RBFNN reduced torque ripple with improved power factor and THD.
Rajesh and Saravanan [17]	ImpJS with crossover and mutationfor torque ripple reduction	ImpJS outperformed PSO, ALO and SSA in terms of voltage deviation

		and MSE
Anshory et al. [18]	PID controller with Firefly algorithm to optimize DC-DC boost converter for solar-powered BLDC	Improved transient response, reduced settling time and eliminated overshoot
Naqvi et al. [19]	Swarm-based optimization for PID tuning in BLDC motors	Achieved reduction in MSE and energy consumption, significantly improving speed control and energy efficiency
Fathima and Vijayasree [20]	Spider Web algorithm for sensored and sensorless torque ripple reduction in BLDC motors	Effectively reduced torque ripple for both sensored and sensorless operations

c) Research Gap and Motivation

While several methods for torque ripple mitigation in BLDC motors have been published, each has its benefits and significant drawbacks. For instance, the integrated converter topology with the ITSA technique successfully reduces torque ripple by combining hybrid control techniques and the Improved Tunicate Swarm Algorithm. Nevertheless, this results in greater processing overhead and system complexity. Similarly, the minimization of torque ripples using the APID controller and the HHO-BWO techniques delivers effective results but requires careful parameter selection, making the method highly sensitive to tuning and adding complexity to the system. For both sensored and sensorless motors, the spider-based controller offers a simple design, but it has scalability problems and might not operate reliably in different operating environments. Moreover, DC-link current management offers a fast, responsive approach to torque ripple reduction, but its scalability and associated trade-offs, such as system efficiency and stability, remain unclear. These limitations indicate a need for a method that combines effective torque ripple reduction with lower system complexity, scalability and robustness across different operating conditions. The proposed BFO algorithm addresses these gaps by providing a robust optimization framework that reduces torque ripple while minimizing computational overhead. BFO's bio-inspired nature allows it to efficiently search for optimal control parameters, making the system less sensitive to initial conditions and tuning. Furthermore, BFO's ability to adapt to dynamic conditions ensures better scalability and consistency, thus addressing the shortcomings of existing techniques.

d) Challenges

Improved system complexity and cost from the integration of extra components, such as specialized control algorithms or hardware modifications, which result in greater manufacturing and maintenance costs, are one way to reduce torque ripple [21]. Reducing torque ripple may require trade-offs between torque smoothness and other crucial parameters like energy economy or maximum torque output. These alterations may also have an impact on the motor's efficiency or performance qualities [22]. Further design considerations and compatibility problems may arise from the inclusion of ripple in torque reduction approaches, which could make system deployment and integration more difficult. This research proposes a BFO-based optimization method for torque ripple reduction in BLDC motors coupled with DC to DC converters in order to address these issues. Because of its versatility, BFO is a good fit for the dynamic conditions that are frequently seen in BLDC motor applications. It enables control parameter adjustments to maintain smooth torque output even in the face of load and speed variations.

e) Contribution

The following is an overview of this manuscript's primary contributions:

- This study introduces an optimization technique specifically designed for BLDC motors integrated with DC-DC converters to mitigate torque ripple effectively.
- The proposed approach employs the BFO Algorithm, which enhances the management of speed and torque inaccuracies in BLDC motors.
- The BFO algorithm is used to properly manage the speed and torque inaccuracy of the BLDC motor.
- This study's primary objective is to significantly decrease the torque ripple in BLDC motors, a common challenge identified in the literature, thereby improving overall motor performance.
- The findings demonstrate that the BFO algorithm outperforms the existing methods in reducing torque ripple and minimizing control error.

f) Organization

The remaining portions of the document is structured as follows: Part:2 Configuration BLDC Motors Integrated with DC-DC Converter. Part 3**:** Proposed Technique for Torque Ripple Minimization in BLDC Motors. Outcomes and discussion are explained in Part 4. The manuscript is concluded in Part 5.

2. Configuration BLDC Motors Integrated with DC-DC Converter

Figure 1 illustrates the configuration of BLDC motors integrated with DC-DC converter. It consists of an oscillator, diode bridge rectifier (DBR), switched inductor and a voltage source inverter (VSI). Initially, an oscillator generates switching signals for the dc -dc converter and the VSI, ensuring synchronized operation. An AC source, such as a battery or the mains, is rectified into DC voltage by a DBR, which then functions as the dc to dc converter's input. In this case, the BFO algorithm minimizes torque ripple by optimizing control parameters like speed and torque. The adjusted parameters are then applied within the converter, which, comprising a switched inductor and control circuit, regulates the voltage level to match the motor's requirements. The switched inductors facilitate energy flow regulation, while the VSI, controlled by the oscillator's signals, transforms DC electricity into 3-phase AC voltage to power the BLDC motor.

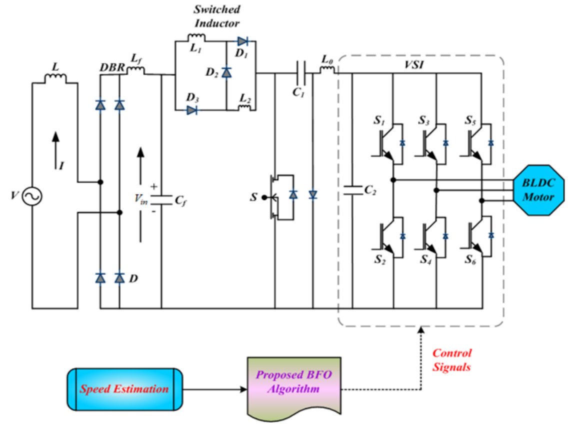

Figure 1. Configuration BLDC Motors Integrated with DC-DC Converter

2.1. BLDC Motor

The torque and speed control analysis is displayed in the BLDC motor modeling [23]. The accompanying voltage condition comprises the electrical dynamics of a brushless DC motor.

$$\zeta^{S}_{abc} = \frac{d}{dt}.\left(FL^{S}_{abc}\right) + \mu^{S}.\varphi^{S}_{abc} \quad (1)$$

here, the stator voltage is represented by ζ, the flux linkage by FL, the stator current by φ, and the stator resistance by μ.

The resistor resistance matrix is calculated separately as,

$$\mu^{S} = \text{diag}[\mu^{S}, \mu^{S}, \mu^{S}] \quad (2)$$

when back-EMF harmonics are present, the electromagnetic torque produced is described as

$$\vartheta^{e} = \sum_{n=1}^{\infty}(2n-1).K_{2n-1}.\begin{bmatrix}\varphi^{S}_{a}\\ \varphi^{S}_{b}\\ \varphi^{S}_{c}\end{bmatrix}.\begin{bmatrix}\cos\left(\theta^{\mu}.(2n-1)\right)\\ \cos\left((2n-1).\left(\theta^{\mu}-\frac{2x}{3}\right)\right)\\ \cos\left((2n-1).\left(\theta^{\mu}+\frac{2x}{3}\right)\right)\end{bmatrix}.\left(\frac{P}{2}.FL_{m}\right) \quad (3)$$

here, ϑ^{e} indicates the electromagnetic torque.

The mechanical dynamic state of the motor speed is calculated as

$$\frac{d}{dt}.\left(\nu^{\mu}\right) = \left(\frac{P}{2}\right).\left(\frac{1}{j}\right).(\vartheta^{e} - \vartheta^{m}) \quad (4)$$

here, the variables ν^{μ}, j, P, and ϑ^{m} denote the rotor angular velocity, a moment of inertia load, and integrated mechanic torque, respectively.The parameters of BLDC motor is given in Table 2.

Table 2. Parameters of BLDC Motor

Parameters	Values
Stator Phase Resistance	0.2 ohm
Stator Phase Inductance	0.0085 H
Flux Linkage	0.175 Weber
Back EMF Flat Area	120°
Inertia	0.089 kgm^2
Viscous Damping	0.005 Nms
Pole Pairs	0.005
Static Friction	4 Nm

2.2. Torque Ripple

2.2.1. Cogging Torque

The pull that permanent magnets have on the stator teeth is what causes cogging torque [24]. Even in the absence of stator winding excitement, it would manifest. The LCM of the stator slot and rotor pole pair numbers yields the cogging torque harmonics. One way to express the clogging torque is as

$$T_{Cog} = \sum_{n=1}^{\infty} T_n \cos\left(24n\theta_m + \alpha_n\right) \quad (5)$$

here θ_m represents the mechanical angle of the rotor., α_n is the cogging torque harmonic's beginning phase angle, and T_n indicates the cogging torque harmonic's magnitude.

2.2.2. Air-gap Flux Harmonics

An electrical machine would experience an additional ripple in torque if air-gap flux harmonics were present [25]. The relationship among the higher harmonic order of 7, 11, 13 and so forth, the basic flux harmonics is mostly to blame for this.The 6th harmonic group in a 3-phase machine is where flux harmonics generate the torque ripple, which may be represented as,

$$\Delta T_{AF} = T_6 \cos 6\theta_e + T_{12} \cos 12\theta_e + \ldots.. \quad (6)$$

2.3. Torque Controller

The reference torque value is used to determine the actual torque error. The torque errors will be used to illustrate the proposed PI controller for choosing the best control pulses for the VSI. [26]. During that process, use the equation to get the ideal torque settings and the VSI control signals.

$$\delta(\Delta) = k_P^n E_t(t) + k_i^n \int E_t(t)dt \qquad (7)$$

here, $E_t(t) = T_i - T_a$. k_P^n and k_i^n are the two parameters of controller. The best torque value is found using the calculation above. The minimizing of torque ripples is also accomplished.
The ripple in torque is reduced by applying the following formula.

$$\rho_R = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}} \qquad (8)$$

where, $T_{\max}$ and $T_{\min}$ denotes the maximum and minimum torque respectively.

3. Proposed Technique for Torque Ripple Minimization in BLDC Motors

This part discusses the proposed BFO method for BLDC motor ripple in torque reduction. The BLDC motor's speed and torque error are managed by the BFO algorithm.

3.1. Bitterling Fish Optimization Algorithm

The bitterling fish is a great example of a naturally occurring strategy for survival. The babysitter for the bitterling fish is the oyster spawning method. To choose the perfect mate, the female bitterling fish looks for a male who is more powerful than other fish. The male species must locate appropriate shells for spawning. They must locate larger oysters with more room for laying eggs. By simulating these fish's mating habits, the BFO method resolves optimization issues [27].The algorithm aims to converge towards optimal control parameters that minimize torque ripple while ensuring safe and efficient BLDC motor operation. By simulating the behavior of bitterling fish searching for optimal solutions in their environment, BFOA effectively explores the parameter space to find control strategies that enhance torque smoothness in BLDC motors. In Figure 2, the BFO flowchart is displayed.
Step 1: Initialization
Set the input factors, such as torque and speed, to zero.
Step 2: Random Generation
After startup, input factors are created at random.It is expressed in equation (9) as

$$X = \begin{bmatrix} x_1^1 & x_1^2 & \dots & x_1^d \\ x_2^1 & x_2^2 & \dots & x_2^d \\ \dots & \dots & \dots & \dots \\ x_n^1 & x_n^2 & \dots & x_n^d \end{bmatrix} \qquad (9)$$

where, d denotes the number of decision variables.
Step 3: Fitness Evaluation
The fitness value is assessed by

$$F = \min(error) \qquad (10)$$

Figure 2. Flowchart of BFO

Step 4: Exploration Phase
This phase involves exploring a range of control parameters, such as PWM duty cycles and the frequency at which the DC to DC converter switches. BFO mimics the behavior of bitterling fish as they explore their environment for optimal resources. In the optimization process, this exploration phase allows the algorithm to uncover various potential solutions that could lead to reduced torque ripple. The status of searchspace is determined by applying equation (11).

$$F_i^{t+1} = \begin{cases} J.F_i^t + \left(F^+ - J.F_i^t\right).\delta & r \le P \\ J.F_i^t + \left(F^* - J.F_i^t\right).\delta & r > P \end{cases} \qquad (11)$$

here, J indicates the number of steps, F^* is the best solution, F^+ is one of the solutions deserving of the randomly selected population, δ and r are random numbers between 0 and 1, and F_i^t and F_i^{t+1} represent the fish's current and new locations.

Step 5: Exploitation Phase

In this phase, the algorithm intensifies its search in the vicinity of the best solutions found so far, aiming to further refine and improve them. Specifically, BFO adjusts the control parameters based on the promising solutions identified during exploration, optimizing them further to minimize torque ripple.

$$F_i^{t+1} = F_i^t + R * rand(0,1) \tag{12}$$

here, the radius of dispersion around the fish's interior shell is represented by the character R.

Step 6: Update the Best Solution

Condition has been updated based on the first and second phases, an iteration of the BFO is considered complete.

Step 7: Termination

If the solution is the best, the procedure gets terminated; if not, it goes back to step 3 fitness evaluations and continues processing the next stages until a solution is found.

4. Results and Discussion

This sector displays the proposed method's performance based on the simulation results. This study recommended minimizing torque ripplein BLDC motors coupled with DC-DC converters using a BFO. The simulation's output is divided into two scenarios, such as Case 1 Analyses of variations in speed (1000, 1500) and torque (3.3) and Case 2: Analysis of variations in speed (1000, -3.3) and torque (3.3, -3.3).The proposed BFO method's simulation is displayed below:

Case 1: Analyses of variations in speed (1000, 1500) and torque (3.3)

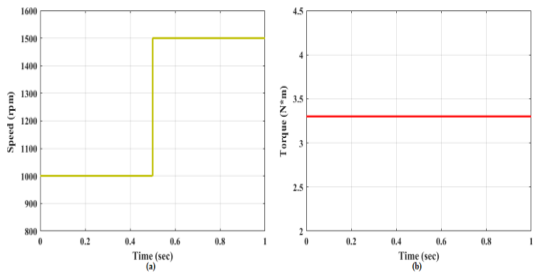

Figure 3. Analysis of reference (a) Speed and (b) Torque

Figure 3 provides an analysis of the torque and reference speed. As seen in Figure 3(a), the analysis's reference speed stays constant between 1000 and 1500 rpm. Figure 3(b) illustrates how the reference torque is maintained at 3.3 Nm.

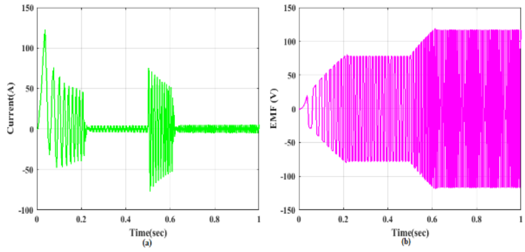

Figure 4. Analyses of (a) Current and (b) EMF

The analyses of EMF and current is displayed in Figure 4. The current flows from 0 to 120A initially and begins fluctuating. The fluctuation starts varying between 80A and -50A as shown in Figure 4(a). The EMF value starts from 0 and reaches 120V at 0.6 s and maintains a constant flow as shown Figure 4(b).

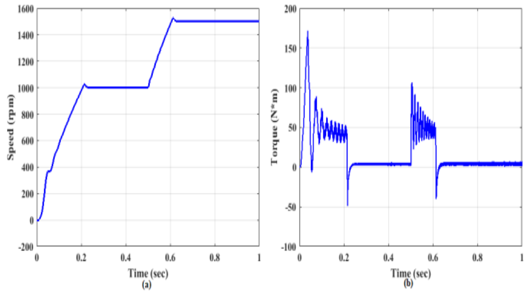

Figure 5. Analyses of (a) Speed and (b) Torque

A speed and torque analyses appears in Figure 5. The speed gradually increases from 0 and maintains a steady rate at 1000 rpm and 1500 rpm as displayed in Figure 5(a). The torque in Figure 5(b) increases from 0 to 160 Nm, varies down to 0 after 0.2 s, and then increases again to 100 Nm after 0.5 s.

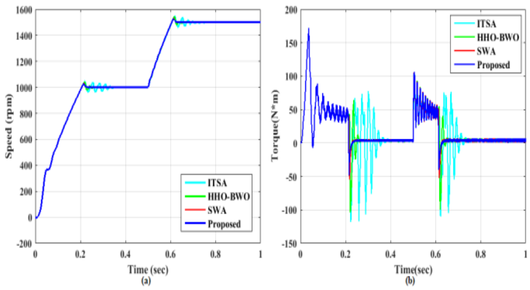

Figure 6. Comparison of (a) Speed and (b) Torque

A comparison between torque and speed is displayed in Figure 6. The speed of proposed method remains constant at 1000 and 1500 rpm while the existing methods have minor fluctuations at this point as displayed in

Figure 6(a). The torque curve for the proposed method, displayed in Figure 6(b), illustrates that it flows from 0 to 160 Nm and stays above 0. At the same time, the torque of existing approaches fluctuates highly between 75 and -120 Nm.

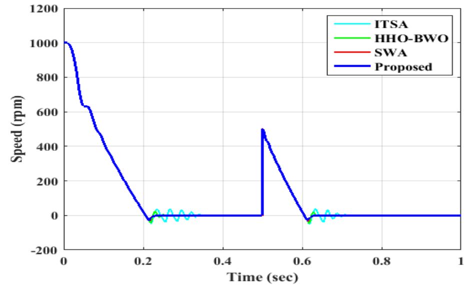

Figure 7. Comparison of Error Speed

CoE speed is shown in Figure 7. The error speed of the proposed method for case 1 is from 1000 to 0 rpm with a minor fluctuation of 500 rpm at 0.5 s. While the proposed method stays constant, the inaccuracy of existing methods varies about 0.

Case 2:Analyses of Variation in Speed (1000) and Torque (3.3, -3.3)

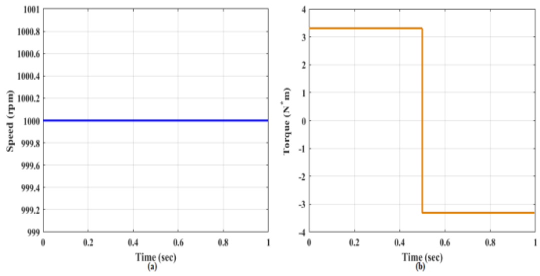

Figure 8. Analyses of reference (a) Speed and (b) Torque

Figure 8 provides an analyses of the torque and reference speed. The reference speed for the analysis is kept at 1000 rpm, as displayed in Figure 8(a). Figure 8(b) illustrates that the reference torque falls between 3.3 Nm and -3.3 Nm.

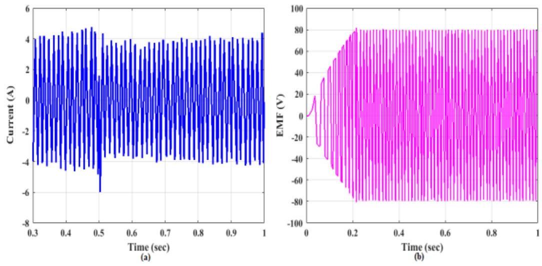

Figure 9. Analyses of (a) Current and (b) EMF

The analyses of EMF and current is displayed in Figure 9. The current constantly fluctuates from 5 to -5 A as shown in Figure 9(a). The EMF value starts from 0 and reaches 80 V at 0.2 s and maintains a constant flow as shown Figure 9(b).

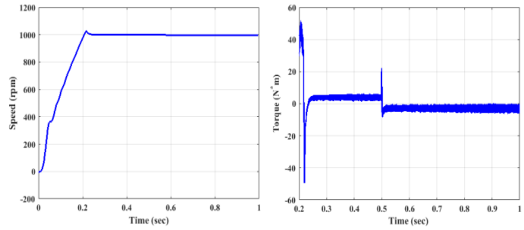

Figure 10. Analyses of (a) Speed and (b) Torque

Analysis of speed and torque is illustrated in Figure 10. The increases the speed gradually from 0 to 1000 rpm and remains constant, as illustrated in Figure 10(a). In Figure 10(b), the torque flows fluctuates between 50 Nm and -50 Nm initially and is kept constant.

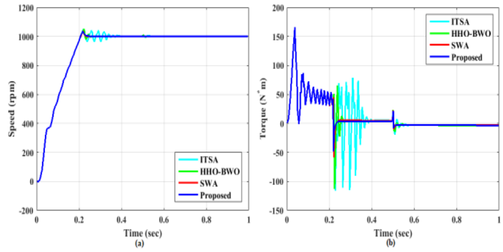

Figure 11. Comparison of (a) Speed and (b) Torque

A comparison between torque and speed is displayed in Figure 11. The speed of proposed method remains constant after reaching 1000 rpm while the existing methods have minor fluctuations at this point as displayed in Figure 11(a). As shown in Figure 11(b), the torque of the proposed method swings back to -50 Nm at 0.2 s after flowing from 0 to 160 Nm. At the same time, the torque of existing approaches fluctuates between positive and negative values after 0.2 s.

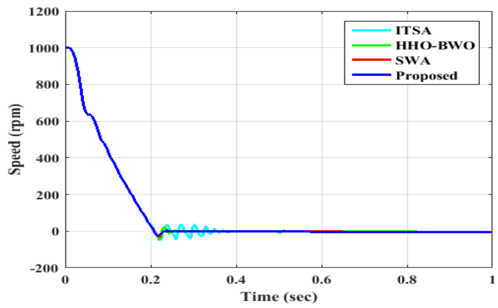

Figure 12. Comparison of Error Speed

CoE speed is illustrated in Figure 12. The error speed of the proposed method for case 2 is from 1000 to 0 rpm and is kept constant. The existing methods error speed experience minor fluctuationswhile the proposed method is maintained constantly at 0.

Table 3. Comparison of Torque Ripple Rate

Methods	Torque Ripple Rate (%)
Proposed	9.64
ITSA	17.32
HHO-BWO	11.20
SWA	22.19

Table 4. Comparison of Error

Methods	Error
Proposed	0.168
ITSA	0.287
HHO-BWO	0.195
SWA	0.311

Comparison of torque ripple rate is given in Table 3. With a torque ripple rate of 9.64, the proposed approach significantly reduces torque ripple. In comparison, the existing methods show higher torque ripple rates asITSA at 17.32, HHO-BWO at 11.20 and SWA at 22.19. The observed decrease in torque ripple highlights the efficacy of the proposed method in enhancing the efficiency of BLDC motors. Comparison of error is given in Table 4. The proposed technique has an error of 0.168 while the existing methods like ITSA, HHO-BWO and SWA has 0.287, 0.195and 0.311 respectively.

4.1. Discussion

The BFO method is proposed for integrating BLDC motors with DC-DC converters to minimize torque ripple. Simulation results demonstrate the system's dynamic behavior under varying conditions, with the reference speed maintained between 1000 and 1500 rpm and a constant torque of 3.3 Nm. Current patterns show an initial rise to 120A, fluctuating between 80A and -50A, while the EMF quickly reaches 120V within 0.6 seconds. Speed and torque analyses reveal a steady speed and torque fluctuation from 0 to 160 Nm, returning to 100 Nm after brief deviations. Comparisons with existing methods indicate superior stability in maintaining consistent speed and torque, highlighting the proposed method's potential for enhanced performance and reliability in practical applications.The comparison results clearly show out the proposed method's improved performance for BLDC motors integrated with DC-DC converters. The proposed method achieves a torque ripple rate of 9.64%, significantly lower than the rates of existing methods such as ITSA at 17.32%, HHO-BWO at 11.20%, and SWA at 22.19%. The proposed strategy’s effectiveness in improving motor stability and reducing mechanical stress during operation is highlighted by this significant reduction in torque ripple. Additionally, the proposed method records an error of 0.168, which is markedly lower than ITSA at 0.287, HHO-BWO at 0.195 and SWA at 0.311. This indicates a higher accuracy in performance control, ensuring closer adherence to desired operational parameters. Overall, these findings highlight the proposed method's potential to significantly improve the performance, stability, and reliability of BLDC motors in practical applications, representing a notable advancement over existing techniques.

5. Conclusion

In this study, an optimization method for BLDC motors coupled with DC-DC converter for torque ripple reduction was developed. The BLDC motor's speed and torque error are managed using the BFO algorithm. The proposed technique’s performance is tested using the MATLAB working environment and contrasted with other existing methods. The simulation result is divided into two cases with different speed and torque values. The proposed BFO algorithm provides better results compared to existing methods such as ITSA, HHO-BWO and SWA.The proposed method achieves a torque ripple rate of 9.64, demonstrating a significant reduction compared to existing methods such asITSA at 17.32, HHO-BWO at 11.20 and SWA at 22.19. The proposed method has an error of 0.168 while the existing methods like ITSA, HHO-BWO and SWA have 0.287, 0.195 and 0.311 respectively.Building on the success of the BFO algorithm for torque ripple reduction, future work should focus on real-world validation through hardware implementation and testing under variable loads. Exploring comparisons with more recent optimization techniques and the adaptability of BFO to different DC-DC converter designs can offer further insights.

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