

Low-cost BLDC drive with PBBO-tuned FOPID controller for enhanced speed regulation and torque ripple reduction

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ABSTRACT

Torque ripple (TR) minimization in brushless DC (BLDC) motors has become a critical research focus due to its direct impact on drive performance, efficiency, and reliability. Conventional BLDC drives typically employ large DC-link capacitors, which increase system cost and weight and are highly sensitive to operating temperature, thereby reducing lifetime. To address these limitations, this work proposes a low-cost capacitor-based BLDC drive integrated with a torque ripple compensation (TRC) technique and optimized control using the probabilistic biogeography-based optimization (PBBO) algorithm. The PBBO method is employed to tune the parameters of a fractional-order proportional-integral-derivative (FOPID) controller, ensuring effective speed regulation and TR reduction. By probabilistically refining migration and emigration rates, PBBO enhances convergence and eliminates redundant species movements, leading to superior controller parameter optimization. Simulation studies validate the proposed PBBO-FOPID approach, demonstrating significant improvements in TR reduction and speed control compared to conventional controllers such as DGOA-FOPID and spider web-based controller (SWC). Results confirm that the PBBO-FOPID controller achieves smoother torque response, reduced ripple, and enhanced speed regulation, establishing it as a cost-effective and high-performance solution for BLDC motor drives.

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1. INTRODUCTION

Brushless DC (BLDC) motors are widely adopted in industrial, automotive, and consumer applications due to their high efficiency, compact design, and superior dynamic performance. However, one of the most persistent challenges in BLDC drives is torque ripple (TR), which arises from the inductive nature of motor windings and the inability of current controllers to generate ideal commutation waveforms under finite DC bus voltage. TR leads to undesirable effects such as acoustic noise, mechanical vibrations, reduced efficiency, and compromised reliability, particularly in sensorless drives where back-EMF harmonics exacerbate the problem. While cogging torque and reluctance torque exert minor influence, the mutual torque remains the dominant factor in ripple generation, making TR minimization a critical requirement for high-performance BLDC systems [1].

Conventional approaches to TR reduction often rely on large DC-link capacitors, which stabilize voltage but introduce drawbacks such as increased cost, weight, and reduced lifetime due to thermal sensitivity. To overcome these limitations, optimization-based control strategies have been explored. Among them, the grasshopper optimization algorithm (GOA) has shown limited effectiveness compared to biogeography-based optimization (BBO). However, traditional BBO suffers from computational inefficiency, as its random immigration and emigration processes frequently result in redundant migrations, slower convergence, and suboptimal solutions.

To address these challenges, this research introduces the probabilistic PBBO algorithm, which enhances the classical BBO framework by probabilistically selecting suitability index variables (SIVs) with significant deviations. This refinement eliminates unnecessary migrations, accelerates convergence, and improves global search accuracy. The PBBO algorithm is employed to optimally tune the parameters of a fractional-order proportional-integral-derivative (FOPID) controller, enabling precise speed regulation and effective TR reduction.

2. PROBABILISTIC BBO METHOD

The normal procedure uses a lot of time because the migration process is carried out without taking this key into consideration. This makes the algorithm expensive to compute and takes up a lot of space. As a result, the suggested work combines the traditional BBO with the probabilistic migration (PM) technique. The difference in the SIVs' levels affects both the immigration rate and the emigration rate in the PM. As a result, only the SIVs that have the most deviations are used in the migration procedure. As a result, the ideal solution can be found rapidly.

In the PM technique, the divergence between the SIV values is used to probabilistically modify the immigration rate (λ_i) and emigration rate (μ_j) [3]. The equation can be used to calculate the element-wise deviation between SIV_{ik} and SIV_{kj} if the set of SIVs represented as SIV_{ik} relates to the SIVs situated in the i^{th} row and SIV_{kj} relates to the SIVs located in the k^{th} row (1):

$$\Pi_k = SIV_{ik} - SIV_{kj} \quad \text{where } k \neq i \quad (1)$$

Further, the minimum deviance values Π_{min} , Π_{max} and $\Pi_{average}$ from the set of deviances are found. $\Pi_{average}$ is computed using (2):

$$\Pi_{average} = \frac{1}{n_H} \sum_{k=1}^n \Pi_k \quad (2)$$

The probability for migration in PM method is computed using (3):

$$\varphi_k = \begin{cases} 0 & \Pi_k = \Pi_{min} \\ 0.25 & \Pi_{min} < \Pi_k < \Pi_{average} \\ 0.5 & \Pi_{average} < \Pi_k < \Pi_{max} \\ 0.9 & \Pi_k = \Pi_{max} \end{cases} \quad (3)$$

The probabilistic immigration rate and emigration rate can be calculated as in (4) and (5) by substituting the value of φ_k obtained from in (1)-(3):

$$\lambda_{k\varphi} = \varphi_k I \left(1 - \frac{K_S(k)}{N_H} \right) \quad (4)$$

$$\mu_{k\varphi} = \varphi_k E \left(\frac{K_S(k)}{N} \right) \quad (5)$$

The PBBO Algorithm 1 is demonstrated below:

Algorithm 1. PBBO algorithm

1. Create initial random habitat set **HAB**_{*i*} as shown in (4).
2. Assign the initial values for the parameters, **Prob**_{Hmod}, **MProb**_{max}, **I**, **E**, **dt**, **N_H**, **©**, **N_{SIV}** and **iter**_{max}.
3. *i* = 1 to *n*
4. Use the fitness function to calculate the HSI for the habitat set "HAB_{*i*}."
5. Select the HAB_{*i*} with the lowest HSI value.
6. End

```

7.  i=1 to  $n_H$ 
8.  j=1 to  $n_{SIV}$ 
9.  k=1 to  $n_H$ 
10. While ( $k \neq i$ )
11. Calculate SIV differences End
12. End
13. End
14. End
15. For k=1 to  $n_H$ 
16. Compute the  $\Pi_{min}$ ,  $\Pi_{max}$  and  $\Pi_{average}$  (2)
17. Compute probability  $\phi_k$  for migration using (4)
18. Use (13) and to calculate the probabilistic immigration and emigration rates (5)
19. End
20. for every habitat between i=1 and  $n_H$ 
21. for k=1 to  $n_{SIV}$ 
22. choose  $HAB_{ik}$  probability proportional to  $\lambda_{k\phi}$ 
23. end
24. For each habitat from j=1 to m
25. for k=1 to n
26. choose  $HAB_{kj}$  probability proportional to  $\mu_{k\phi}$ 
27. Replace  $HAB_{jk}$  with  $HAB_{ik}$ 
28. end
29. end
end

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3. SPEED CONTROL AND TORQUE RIPPLE REDUCTION IN BLDC MOTOR WITH OPTIMIZED PBBO-FOPID

In this research, the integral of time absolute error (ITAE) parameter includes speed error and torque error as given in the fitness/objective function. The implementation of the PBBO-tuned FOPID for the TRC method is presented in Figure 1.

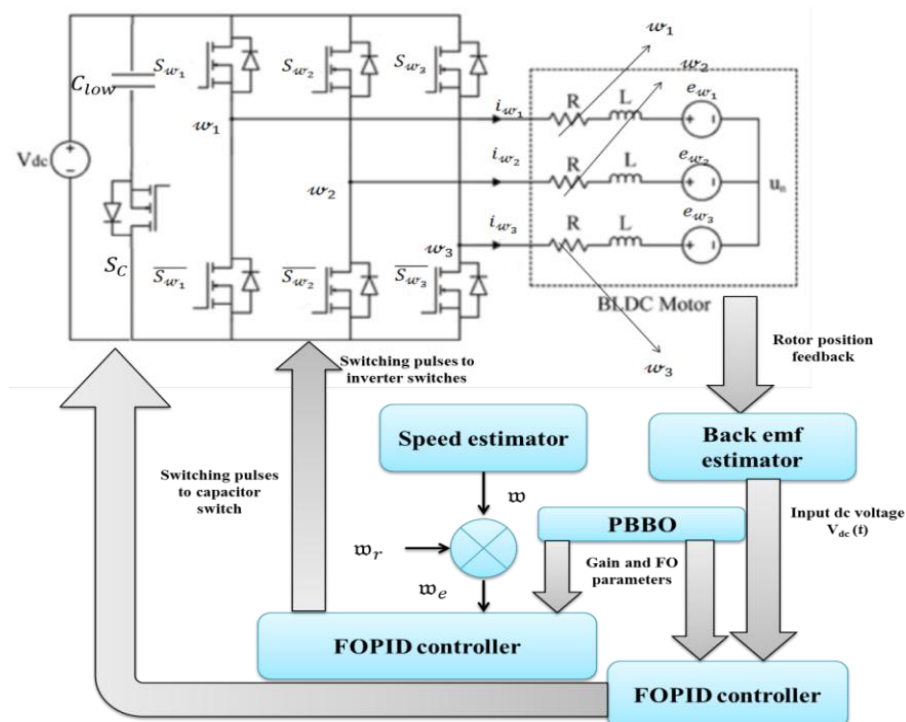


Figure 1. Implementation of the proposed technique with PBBO-FOPID controller

The PBBO algorithm's goal is to reduce this objective function. The gain parameters of the PI controller, such as K_P , K_I , K_D , λ , and μ , are calculated using the PBBO method in order to achieve this fitness

[4]. For the obtained gain parameter values, the fitness functions are computed. If they are minimum, the values are considered as solutions to the gain values of the PI controller [5]. The reason for tuning the PI controller to satisfy the fitness function is to make the steady-state error zero (minimum value). The habitat set in BBO has been considered as the set of SIVs where SIVs correspond to K_p , K_i , K_D , λ , and μ for this problem. Since there are five controller parameters for tuning, the number of SIVs in the process is equal to five. Hence, HAB_i can be represented as in (6).

$$HAB_{ij} = \begin{bmatrix} K_{p1} & K_{i1} & K_{D1} & \lambda_1 & \mu_1 \\ K_{p2} & K_{i2} & K_{D2} & \lambda_2 & \mu_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ K_{pn_H} & K_{in_H} & K_{Dn_H} & \lambda_{n_H} & \mu_{n_H} \end{bmatrix} \quad (6)$$

HAB_{ij} is assigned for the two controllers separately, since each of them is tuned separately.

The fitness function for this application can be computed in (7).

$$HSI = \begin{cases} ITAE_1 & \text{for } FOPID_1 \\ ITAE_2 & \text{for } FOPID_2 \end{cases} \quad (7)$$

Using the PBBO algorithm provided and the optimal solution set consisting of $\{K_p, K_i, K_D, \lambda, \mu\}$ is selected based on the fitness function value. Based on the BLDC motor's observed properties, the inner loop is utilised to synchronise the back emf of the BLDC motor with the inverting gate signal. By adjusting the DC bus voltage with a PWM inverter, the speed of the BLDC motor is controlled by the outer loop. Table 1 displays the initial PBBO parameters taken into account in this application [6].

Table 1. The PBBO's initial parameters were taken

S.L.	Parameters	Value
1.	$Prob_{Hmod}$	0.001
2.	$MProb_{max}$	0.005
3.	E	0.5
4.	I	0.8
5.	dt	0.1 to 2
6.	N_H	50
7.	$iter_{max}$	100

4. RESULTS AND DISCUSSION

The BLDC motors have employed pulse width modulated voltage source inverters (PWMVSI) as drivers. This configuration typically requires additional DC link elements. The voltage across this DC link influences the quality of the output and customarily produces harmonics. Furthermore, the harmonics produced by back EMF are reduced, since the presence of TR in the BLDC motor is undesirable. The proposed TRC method with PBBO-FOPID is validated by simulating the system in MATLAB. The results of phase current, back emf, torque, and speed response in the time domain are obtained for evaluating the TRC method with PBBO-FOPID. Moreover, the performance is improved by using the proportional-integral-derivative (PID) controller, which provides less settling time and good steady-state accuracy [7]. The results are compared with the BLDC drive with a small capacitor and the TRC method with Table 2 provides the FOPID controller tuning values for the TRC, BLDC motor speed control implementation, and ITAE value. Also, the TR values (%) for the application of various controllers are noted and summarised.

Table 2. Optimal values of controller parameters for different OAs with PBBO-FOPID

S.L	Controller	K_p	K_i	K_D	λ	μ	ITAE
1.	PID	1.174375	0.052263	1.171163	-	-	0.009161
2.	Fuzzy PID	0.563075	0.736217	0.235561	$\alpha = 0.440$	$\beta = 2.534$	0.00461
3.	FOPID	0.540214	0.080536	0.52386	0.878865	0.691278	$8.156e^{-3}$
4.	GA-FOPID	0.226872	0.044581	0.386011	0.861036	0.44545	$4.56e^{-5}$
5.	PSO-FOPID	0.517053	0.62446	0.951254	0.601104	0.888747	$2.87e^{-5}$
6.	BBO-FOPID	0.367702	0.504018	0.670135	0.754763	0.888683	$5.89e^{-6}$
7.	GOA-FOPID	0.151542	0.165016	0.514106	0.835121	0.317221	$2.74e^{-6}$
8.	DGOA-FOPID	0.48024	0.565321	1.475046	0.510681	0.882828	$1.985e^{-6}$
9.	PBBO-FOPID	0.074427	0.13476	0.45865	0.828307	0.235515	$5.845e^{-7}$

The phase current, DC link voltage, speed response and torque response curves are observed for the proposed PBBO-FOPID. Also, the comparative analysis graphs for the following cases are also performed and illustrated [8]. Figure 2 represents the variation of phase current $i_m(t)$ achieved by using TRC method with PBBO-FOPID where the number of ripples is very less. The proposed method provides better compensation with low-cost capacitor.

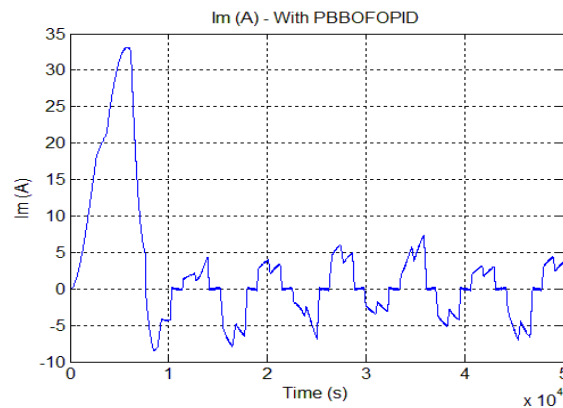


Figure 2. Response of phase current i_m for BLDC motor drive with small capacitor and PBBO-FOPID

During an extended period, the phase current is continually maintained. Figure 3 provides a comparison of phase current compensation in various scenarios. From Figure 3, it can be seen that the waveform has less ripples than in the other situations. Also, the higher current is gradually obtained and the higher value is formed in the steady state. Also, it is accomplished in a controlled, easy way [9].

Figure 4 represents DC link voltage for TRC with PBBO-FOPID. In this case, though the voltage suddenly rises to a larger value, when reaching a steady state, it shows almost negligible ripples in the waveform and it can be observed in Figure 4. The waveform resembles almost as a constant DC voltage.

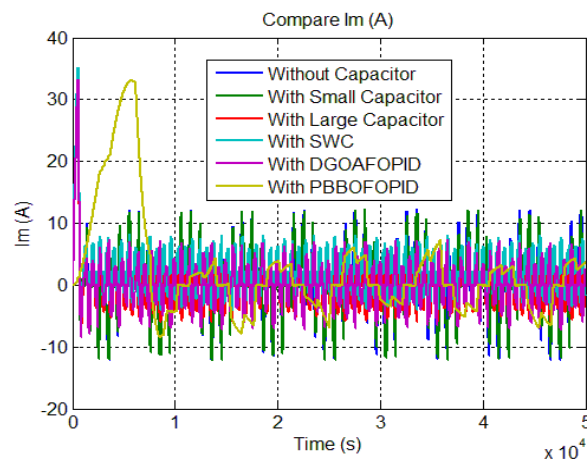


Figure 3. Comparison of phase current for different cases with PBBO-FOPID

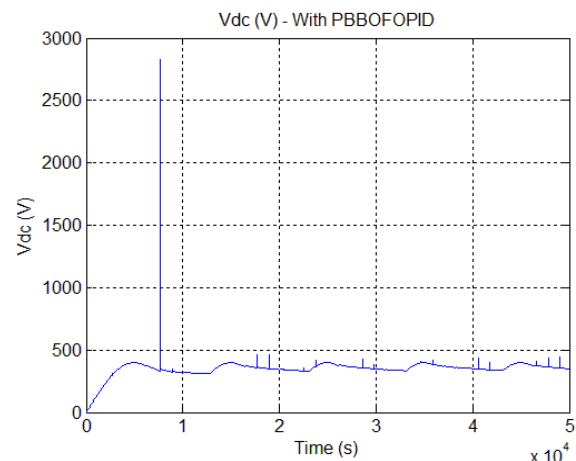


Figure 4. V_{DC} for BLDC motor drive with small capacitor and PBBO-FOPID

Figure 5 provides a comparison of DC link voltage correction in various scenarios. From Figure it can be seen that the waveform has fewer ripples than in the other scenarios. Also, it is implied that the proposed work has less fleeting errors [10]. The torque response for TRC with PBBO-FOPID is shown in Figure 6. Even though the torque value increases in this instance, it gradually decreases before reaching a steady state with just minor ripples. This figure suggests that the torque curve eventually reaches steady state after an abrupt large rise. Figure 7 shows the comparative analysis of torque response for all methods. From which, it is observed that the proposed method provides better TR compensation, due to the improved

performance of PBBO-FOPID. Figure 8 represents the variation of motor speed for TRC with PBBO-FOPID. In this Figure the speed reaches the set point in a smooth manner. It favours smoother operation of the motor and it does not exhibit any overshoot in the speed response. The comparative analysis of speed for all approaches is shown in Figure 9. It is evident from Figure that the speed exhibits fewer ripples. The speed increases linearly until it reaches the rated value.

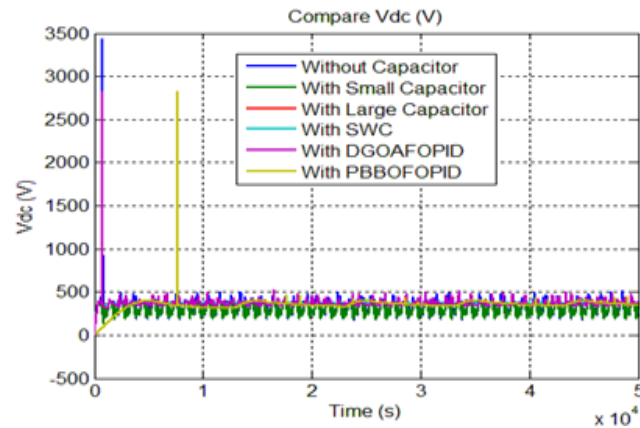


Figure 5. Comparison of DC link voltage in all cases with PBBO-FOPID

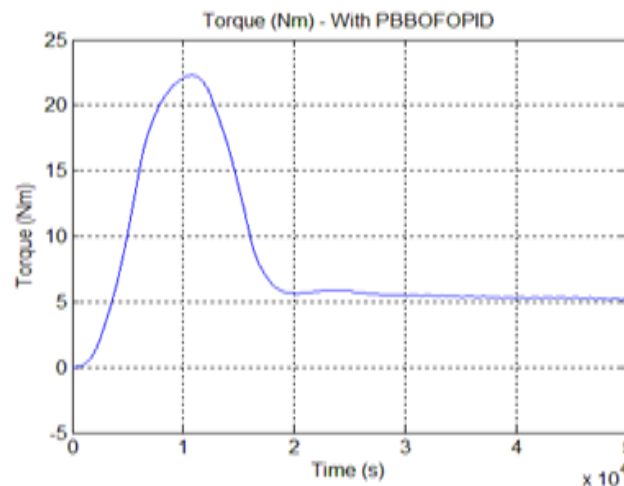


Figure 6. Torque response for tiny capacitor BLDC motor driving and PBBO-FOPID

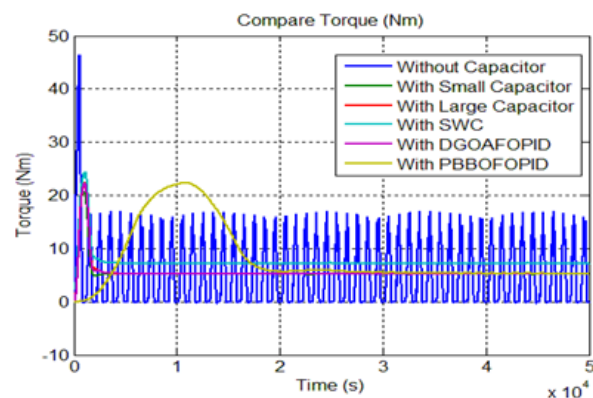


Figure 7. Comparative analysis of torque response for all methods with PBBO-FOPID

Also, the TR and THD of the proposed controller as well as the various controllers are noted and contrasted with the THD values obtained from various situations, such as drives with no capacitor, drives with a large capacitor, and drives with a tiny capacitor. Table 3 shows a study of the TR values and the THD present in the motor output for various instances [11].

When a large capacitor based drive is employed, TR is completely reduced whereas, without DC link capacitor based drive, 100% of TRs exists, and it is not reduced. In the work of Ransara&Madawala (2015), low DC link capacitor is employed and it is observed that 8% of TRs is present [12]. In the proposed work, to quickly reduce the torque, SWC is employed and only 7% of TRs is present. When DGOA-FOPID is employed with TRC technique, TR becomes 4.74% whereas it is 7.1% when the conventional FOPID is employed and 5.4% when GOA-FOPID is employed for TRC is mentioned Table 3.

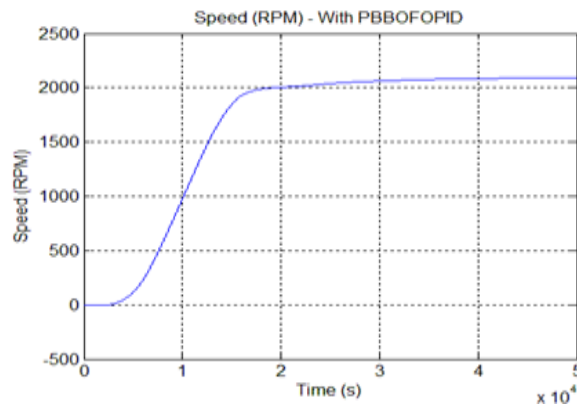


Figure 8. Speed response for BLDC motor drive with small capacitor and PBBO-FOPID

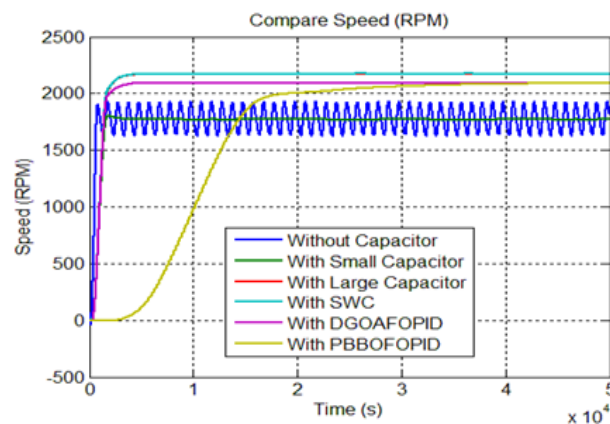


Figure 9. Comparative analysis of speed for all methods with PBBO-FOPID

Table 3. Comparative analysis of THD and TR for different methods with PBBO-FOPID

S.L	Case	THD (%)	TR (%)
1.	With large capacitor	203.4	0
2.	Without capacitor	114.3	100
3.	With the small capacitor (TRC) (Ransara&Madawala 2015)	105.6	8
4.	TRC-FLC	98.9	8
5.	TRC-SWC	98.7	7
6.	TRC-PID	99.5	8.1
7.	TRC-Fuzzy PID	99.1	7.3
8.	TRC-FOPID	99	7.1
9.	TRC-GAFOPID	98.5	6.4
10.	TRC-PSOFOPID	98.1	6
11.	TRC-BBOFOPID	97.7	5.6
12.	TRC-GOAFOPID	97.1	5.4
13.	TRC-DGOAFOPID	96.5	4.74
14.	TRC-PBBOFOPID	95.1	3.78

5. CONCLUSION

This research presents a low-cost capacitor-based TRC drive for BLDC motors, optimized through a PBBO-tuned FOPID controller. The proposed PBBO-FOPID approach effectively enhances both speed regulation and TRR, outperforming conventional optimization methods such as GA, PSO, BBO, GOA, and DGOA. Simulation results confirm that the PBBO-FOPID controller achieves smoother torque response, reduced ripple, and improved speed stability compared to existing TRC techniques. Quantitative analysis demonstrates that TR is reduced to 3.78%, representing a 52.75% improvement over the low-cost capacitor-based BLDC drive with the TRC method reported by Ransara & Madawala (2015). Furthermore, the proposed scheme achieves a 46% reduction compared to TRC-SWC and a 20.25% reduction compared to TRC-DGOA-FOPID. The adoption of a small capacitor instead of a large DC-link capacitor significantly lowers system cost while maintaining effective compensation. By ensuring continuous phase current and minimizing discontinuities, the PBBO-FOPID controller establishes a robust framework for cost-effective, high-performance BLDC motor drives.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nvestigation

R : **R**esources

D : **D**ata Curation

O : **O**riting - **O**riginal Draft

E : **E**riting - **R**eview & **E**editing

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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