Performance enhancement of brushless direct current motor under different novel optimization techniques

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ABSTRACT

This research paper presents a novel attempt of speed control for brushless direct current (BLDC) motor in low power/servo motor applications. The performance is measured based on the swiftness for the recovery of desired speed amidst in disturbances, sensitive to supply/motor load fluctuations. The proportional integral (PI) controller is competent only for linear time invariant systems. The state of art technology is, PI controller is used with metaheuristic optimization algorithms viz. Honeybee mating optimization (HBO), artificial immune system (AIS), and frog leaping guided algorithm (FLG), for fine tuning of gain coefficients. Earlier literature survey shows power quality and time domain specifications for separate applications. An innovative approach for the assessment of performance indicators like maximum overshoot (M_p), settling time (t_s), power factor (PF) and total harmonic distortion (THD) simultaneously in the optimized PI controller is suggested. By avoiding local optima trapping, this method gives better dynamic performance for various test conditions. MATLAB/Simulink 2021a software is utilized in the examination of performance in various load and speed scenarios, subsequently validated with hardware where cost effective Arduino controller replaced programmable interface controllers (PIC) microcontroller.

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1. INTRODUCTION

New developments in compact motors have recently resulted from the introduction of sophisticated power electronic devices and contemporary control engineering. Their straightforward and economical speed-controlling techniques and linear speed-torque characteristics have helped direct current motors account for more than 70% of fractional horsepower motors used in the electrical sector [1]. However, direct current (DC) motors have palpable drawbacks as well, like a shorter lifespan due to mechanical friction across the brushes and commutator [2]. On the other hand, the permanent magnet synchronous motor (PMSM) in this brushless direct current (BLDC) motor is electronically commutated. It is made up of three armature coils in the fixed section and special magnets (rare earth) contained in the spinning part. Compared to PMSM, which has a sinusoidal counter-electromagnetic force (counter-EMF) waveform structure, it has a non-sinusoidal (counter-EMF) and 15% more power density [3]. Using an electronic regulator, BLDC motors eliminate a common defect seen in many conventional electric drives, namely the mechanical commutator (brushes). However, this restricts the motor's size and output. Therefore, for this motor drive circuit an accurate and complex actuator controller was required.

The strong performance and resilience of the BLDC market drive its remarkable expansion. Prior to 2030, BLDC motors will replace other drives due to their increasing popularity [4]. Reduction in electrical connections, mechanical misalignments, final product size, and weight, the development of BLDC motors is expected to improve product durability and dependability. Automobiles, electric trains, robotics, aerospace, home appliances, computer peripherals, the food and chemical industries, healthcare equipment, and many more industrial applications are a few of the many uses for it [5].

The primary factors that have palpable influence on the tracking and regulation of BLDC motors include controller design [6] and controller gain optimization [7]. The use of highly effective controllers of a small number and innovative control strategies is seen in literature for a change in motor behavior, with focus on either power quality or time domain specification as the research gap. This study is related to the investigation of the effects of Time domain characteristics, viz., ts, M_p, $E_{ss,}$ tr and power quality issues viz., power factor (PF) and total harmonic distortion (THD) simultaneously as a novel attempt. A variety of speed controllers and state-of-the-art controlling techniques have been used for solving this problem. Metaheuristic optimization is a unique technique that can handle uncertainties and nonlinear parameters. Hence it has been used for the fine tuning of the controller gains considering its ability to provide appropriate solutions for the problems increased in nonlinear programming-hard situations [8]. The three contributions to improve the dynamic properties of BLDC drives are listed below.

- The artificial immune system (AIS), honeybee mating optimization (HBO) control system is intended for analysis of the controller's performance in terms of several metrics related to motor dynamics.
- The frog leaping guided (FLG) algorithm, sometimes known as “Frog jumping algorithm” is a powerful optimization technique in the drive circuits.
- Comparison with results seen in hardware, helps verification of the behavior of the motor with the use of the simulated outcome.

The paper is organized as follows: section 2 deals with outline. Section 3 discusses speed controllers that use different unique optimizations such as HBO, AIS, and FLG. Section 4 refers to results and discussion; section 5 presents the hardware design and results. Section 6 reflects the conclusions to ensure that it meets the benchmarks set by the IEEE standards by comparing with simulated results.

2. WORK-OUTLINE

Various metaheuristic algorithms with inspiration from nature have been developed recently for maximation of the control system gains of BLDC motors. Smart computing techniques are becoming increasingly popular in control engineering, as demonstrated [9]. It has been suggested the adaptive fuzzy proportional–integral–derivative (PID) control speed for improvement in the speed control characteristic of the BLDC drives [10]. An adaptive fuzzy logic controller (FLC) and a simple PID controller are components of the suggested system. This method uses genetic algorithm (GA) for the fine turning of the controller gains for the management of speed of the BLDC motor till reaches a specific steady state condition. A GA optimization fuzzy-PID controller for improvement in behavior created [11], adaptive factor, multi-objective equation and improved differential evolutional (DE) approach are used to optimize the gains of the controller [12].

Particle swarm optimization (PSO), is a method for increasing controller goals [13]. The study demonstrated that, in comparison to GA-based controllers, the suggested PSO based algorithm produced lower levels of overshoot (63.94%), peak time (0.26 seconds), and correction time (1.4 seconds). According to these findings, choice of the controller's parameter has a major impact on performance. The authors used a traditional approach with this algorithm for the application of drives. Using an enhanced DE approach, Beig *et al.* [14] suggested switching pattern for pulse width modulation technique to control speed.

The successful application depends upon component identification in power converter based on application [15]. This technique is used to achieve the minimizing error while maximizing controller gains. Salp swarm optimization algorithm was proposed for BLDC motors with sensors [16]. In order to maximize the benefits of a conventional controller, an adjustable speed and power factor correction controller is proposed [17], however they did not analyze the THD. A grey wolf optimization technique was presented for the optimization of the gains of the proportional–integral (PID) controller of BLDC motors [18]. Simultaneous analysis of the time domain specifications and power quality issues through optimization is the need of the hour as shown in Figure 1. This will ensure higher impact in the drive system. IEEE standard 519-2014 recommends the harmonics limits, lower THD implies low electromagnetic interference (EMI), low heating and low iron core loss. Stator voltage harmonics can generate torque ripple, which impedes smooth operation and increases heat and in addition to that positive sequence component is responsible for overheating and negative sequence component is responsible for torque ripple.

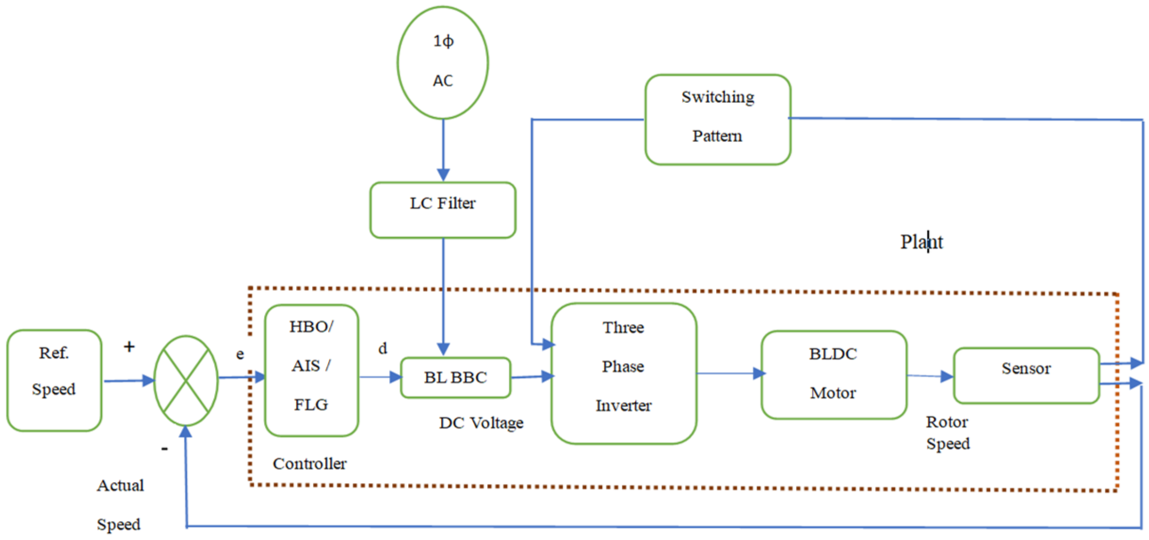

Figure 1. Structure of controller

3. SPEED CONTROLLER USING VARIOUS OPTIMIZATIONS-SIMULATED RESULTS

3.1. Honeybee mating optimization (HBO tuned controller for BLDC motor)

A goal of optimization-based solutions in this digital era is to reduce manual labor and solution time. Researchers have produced a plethora of software packages that achieve this dual benefit. Honey bee mating optimization [19] is employed as a soft computing method where iterations are carried out until the desired speed is reached.

Annealing function for queen probability, accept i^{th} drone to mate and improve trial solution is,

$$P\ (Queen, Drone) = e^{\left[\frac{-\Delta(fi)}{energy(t)}\right]} \tag{1}$$

$\Delta(f)$ refer, modulus value of fitness difference with drone and queen. When mating flight is in progress both queen's speed and energy reduce simultaneously after each iteration.

$$energy\ (t+1)\ =\ \infty\ x\ energy\ (t) \tag{2}$$

where t € $[0, 1, 2, \dots t]$ and decay rate $0 < \infty < 1$

$$speed\ (t+1) =\ energy\ (t) - \beta\ where\ t\ € \ [0, 1, 2 \dots . t]$$
$$and\ decay\ rate\ \beta\ within\ [0, 1] \tag{3}$$

Queen updates its energy and speed with the use of (2) and (3). Mating flight ends when the energy level falls below a threshold value (close to zero).

– Queen: Highest weightage in the cluster at the current instant.
– Drone: Low weightage

3.2. Artificial immune system

Life becomes fatal in the absence of immune system. AIS mimics' human immunology applied to complicated issues. A single antigen can be recognized by several antibodies. As shown in Figure 2, AIS distinguishes between antigen and antibody; this phenomenon is utilized as a tool for nonlinear and time variant applications [20]–[22]. The following steps are involved in the process.

a. Initialization

Antigen-value to be optimized is objective function $f(x)$ and antibodies-corresponding solution to the problems.

b. Cloning

$$Antibodies\ are\ cloned\ based\ on\ the\ fitness, NC\ = \Sigma\ (\beta * j/i) \tag{4}$$

where $i = 1, 2, 3 \ \dots n$, NC is clone number, β means multiplier factor, and j refers antibodies population size.

c. Hyper mutation

Clones are mutated in inverse proportion of affinity and N antibodies-selected for the next iteration. If antibodies match antigen (threshold value) then concentration increases 'stimulation' if not concentration decreases 'suppression'.

d. Repeat

Introduce a random number till antibodies are generated.

e. End

Stopping criteria met, i.e., antibody concentration will nullify antigen.

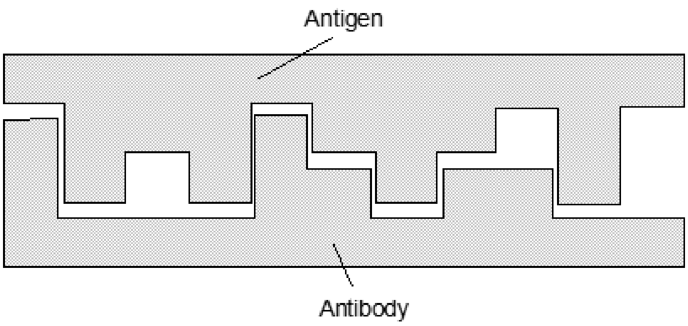

Figure 2. Antigen nullified by antibody

3.2. Frog leaping with global guided algorithm

This study has developed a metaheuristic method called frog leaping with global guided optimization (FLG) meant for a change in gain coefficients for control. The global best frog will be replaced by worst frog for the creation of FLG, the global best frog is used in place of the worst frog. Memes in FLG therefore spread at a quicker rate of convergence. The optimal values of the scaling factors, namely $K_p$and K_i of the controller, are ascertained using the proposed FLG. This approach has been verified through simulations and contrasted with real-world BLDC drive implementations.

A swarm of frogs has been used in FLG's population-based, evolving metaheuristic, which maximizes prey [23]–[25]. Its integration of a memeplex algorithm based on genetic evolution with particle swarm optimization (PSO) is a major factor in its success. The PSO algorithm serves as the foundation for this method's local exploration, and the idea is integration of data from concurrent local searches originates from the shuffling complex evolution methodology. Frog population shows a cluster of potential solutions in FLG. The frog sets were divided into several mimetics' groups, each of which represents an exclusive temperament. The frogs tend to congregate at what appears to be the best; this is just provisional and could be a local optimum. However, some memetics were taken in sub-memetics to avoid entrapment in local optima. It is best to move the frog that is at the worst place. A new group known as memeticists has been developed throughout memeplex iterations. FLG steps involved are.

a. Population creation: The initial population (frogs) is defined as

$$P = \{p_i, f_i, \ \ i = 1,2,3 \dots .F\} \ within \ the \ exploration \ area,$$

where p_i is the position of i^{th} frog and f_i represents its fitness. The fitness values are arranged in decreasing order.

b. Splitting the memetics: Divide the population into n memeticists $\{Q_1, Q_2, Q_3 \dots \dots Q_n\}$, each contains n frogs and

$$Q_i = [(p_j, f_j)] \mid p_j = p_{j+n(j-1)}, f_j = f_{j+n(j-1)} \tag{5}$$

where $j = 1,2,3 \dots \dots m$.

c. Submemetics creation: The strategy selection of a submemetics (fork frogs) in every memeticists has larger parameters distributed in good locations. Better position in frog strategy has greater weights allocated to submemetics having triangular probability distribution as (6).

$$w_i = \frac{2(m+1-i)}{m(m+1)}, \quad i = 1,2,3 \dots, m \tag{6}$$

d. Submemetics evolution: Letp_{best} is the best location and p_{worst} is the worst location in submemetics. Then, local exploration starts from the worst frog to leap in best group. The current position is updated by one leaping step as shown in (7).

$$l^{g+1} = \begin{cases} \min\{\mathrm{int}[r^g(p^g_{best} - p^g_{worst})], l_{max}\}, \text{if } p^g_{best} \geq p^g_{worst} \\ \min\{\mathrm{int}[r^g(p^g_{best} - p^g_{worst})], -l_{max}\}, \text{if } p^g_{best} < p^g_{worst} \end{cases} \tag{7}$$

where $int(.)$ denotes the integer function which converts the specified value into an integer number; $\min(.)$ function returns the item with the lowest value in an iterable; l_{max} is maximum leap size; r- random number and g-evolution generation. Moreover, if the current location is better than worst frog, then worst frog's position is modified as

$$p_t^{g+1} = p_t^g + l^{g+1} \tag{8}$$

Else, the worst frog position becomes global optima hence

$$l^{g+1} = \begin{cases} min\{int[r^g(p^g_{sbest} - p^g_{worst})], l_{max}\}, if\ p^g_{sbest} \geq p^g_{worst} \\ min\{int[r^g(p^g_{sbest} - p^g_{worst})], -l_{max}\}, if\ p^g_{sbest} < p^g_{worst} \end{cases} \tag{9}$$

where p^g_{sbest} is best position of the swarm. In case if the worst frog fails to improve its position, a random position is automatically generated to replace it

$$p_t^{g+1} = b_1 + int[r^g(b_1 - b_2)] \tag{10}$$

where $[b_1, b_2]$ - boundary for possible location of frogs. Then, frogs are sorted in decreasing order, ascertained on eligibility. Above steps are repeated till submemetics G_1 is formed.

e. The remaining memetics have been rearranged in the decreasing order of fitness on completion of this local investigation. This is known as memeticists shuffling. Until memetic evolution generation G_2 is reached, the group is divided into memeticists, and the local exploration process is carried out repeatedly.

4. RESULTS WITH DISCUSSION

Using MATLAB/Simulink 2021 software, the BLDC drive circuits were designed for the verification of the speed of this innovative approach. Using the FLG technique, the effectiveness of speed control for BLDC drives is confirmed under various test scenarios. The AIS and HBO are seen as two further sophisticated control systems with the performance of comparison with FLG controller. All the three algorithms were utilized until the results were obtained. Three distinct instances have been taken into consideration for analysis of the performance of the suggested control system: i) speed response for constant load, ii) speed response for step change in load, and iii) response for variable speed. In optimizations the computation time of algorithm is proportional to constraints, it proceeds iteratively selecting a new solution until predefined halt condition is met.

4.1. Speed response for constant load

4.1.1. Simulation results

BLDC motors are designed for continuous duty. Interaction of the magnetic forces of permanent magnet (rotor) with electromagnetic field of armature (Stator) is seen in the production of torque. The load torque during a load test which should be identical to the operating torque, is determined by the duty cycle (d) which the controller generates based on the speed error, as illustrated in the block diagram Figure 1 below. For different optimization strategies, Simulation predicts performance for different optimization strategies with the use of static loading at 25%, 50%, 75%, and 100% of full load. Table 1 and Figures 3 to 5 suggest that FLG is strong robustness, improved convergence speed than to HBO and AIS. The algorithm should choose "d" as the ideal value considering increasing the switching frequency will result in more pulse width modulation (PWM) losses and decreasing it will result in less system bandwidth, which could harm the drive system or cause stoppage of the motor.

Table 1. Performances for different loading @ 2000rpm

Method	Performance metrics	25%	50%	75%	100%
		I=0.3A	I=0.6	I=0.9	I=1.2A
HBO	THD	15.94	16.2	18.22	20.71
	M_p	80	140	210	260
	T_s	0.6	0.8	0.9	1
	PF	0.9364	0.9274	0.921	0.9142
AIS	THD	13.28	14.3	15.7	17.25
	M_p	40	100	140	160
	T_s	0.5	0.16	0.2	0.25
	PF	0.9586	0.951	0.9475	0.9361
FLG	THD	7.67	11.96	12.4	13.62
	M_p	30	80	120	150
	T_s	0.09	0.1	0.15	0.2
	PF	0.988	0.98	0.974	0.971

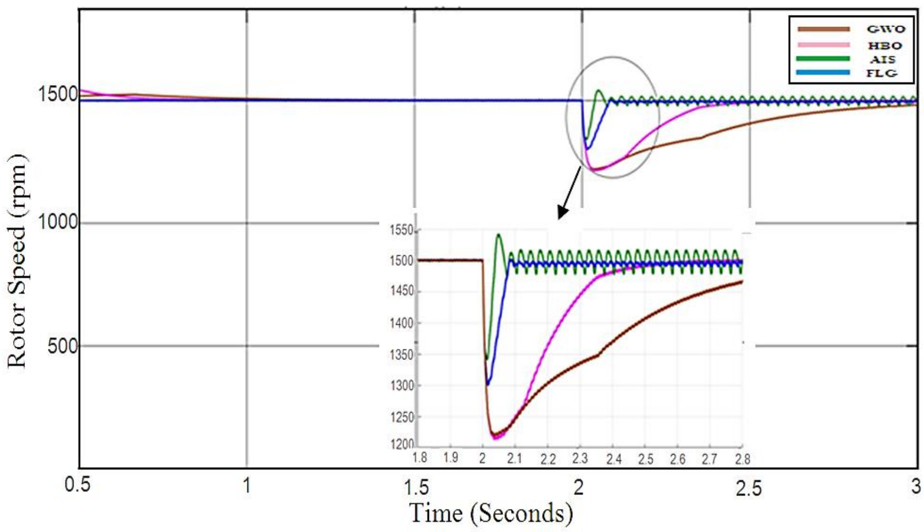

Figure 3. Speed response of BLDC motor @100% loading

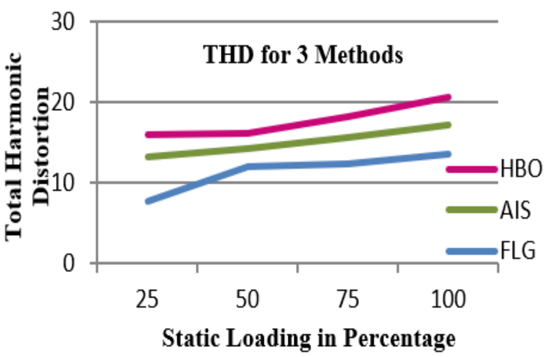

Figure 4. THD comparison for static loading

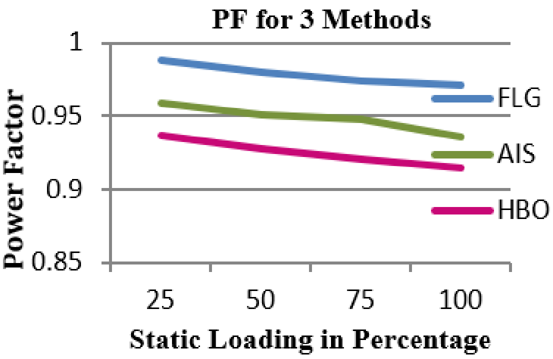

Figure 5. PF comparison for static loading

4.2. Response for step change in load using optimizations

As shown in Figure 6 and Table 2, FLG performs better than other methods for different step changes in loading under different optimizations. Induction or electromechanical energy conversion is the same operational principle that underpins all electrical motors, regardless of their various kinds and sizes. Fast Fourier transform (FFT) analysis in MATLAB is used in the measurement of THD (IEEE standard 519-2014 recommends the harmonics limits, lower THD implies low EMI, low heating and low iron core loss in motors), done in addition to PF in BLDC motors, considering the menace of THD for the overheating of windings that trips relays. Step changes in loading, such as pressing, cutting, and drilling, can benefit from the step change in load analysis.

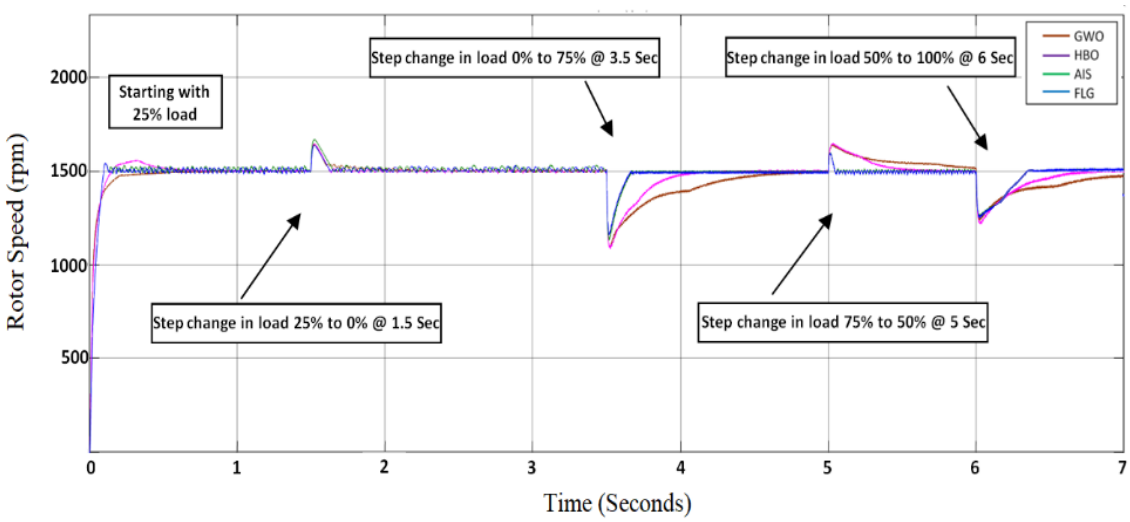

Figure 6. Speed responses for step change in load using optimization techniques

Table 2. Performances for step change in load

Method	Metrics	25-0%	0-75%	75-50%	50-100%
HBO	M_p	80	220	75	200
	T_s	0.50	0.70	0.60	0.65
	PF	0.961	0.952	0.948	0.945
AIS	M_p	75	210	55	120
	T_s	0.30	0.40	0.30	0.45
	PF	0.973	0.965	0.917	0.957
FLG	M_p	70	110	50	100
	T_s	0.20	0.30	0.20	0.40
	PF	0.989	0.973	0.990	0.971

4.3. Response for variable speed

This research is most helpful for getting an understanding of the dynamics of an electric train during its three phases of operation: acceleration, running, and braking. The goal is to provide passengers with a comfortable ride while causing the least amount of wear and tear on the moving parts. The simulation's output and waveforms shown in Figure 7 and Table 3 demonstrate the outperformance of the FLG-sponsored optimization method with the other two methods in terms of T_s, M_p, PF, and THD.

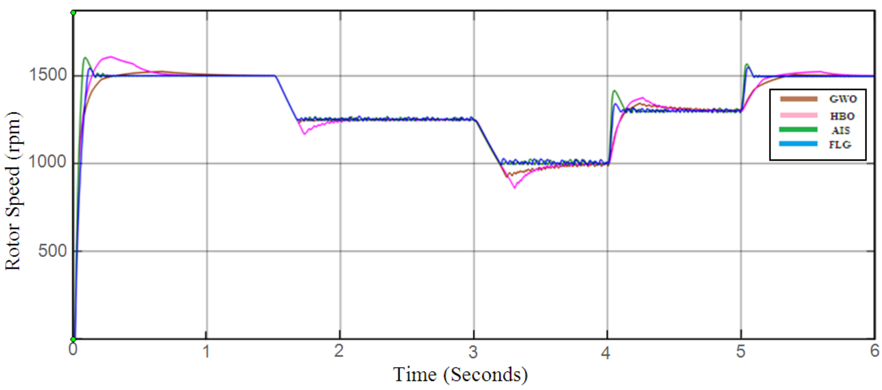

Figure 7. Speed responses for variable speed @ constant (FULL) load using optimization techniques

Table 3. Speed change @ constant (full) load

Method	Performance Metrics	0 to 1,500	1,500 to 1,250	1,250 to 1,000	1,000 to 1,250	1,250 to 15,00
HBO	M_p	225	100	90	125	120
	T_s	0.7	0.5	0.5	0.6	0.6
	PF	0.958	0.962	0.970	0.973	0.965
	THD	20.71	19.63	17.88	19.12	20.67
AIS	M_p	200	10	10	100	115
	T_s	0.3	0.15	0.15	0.25	0.15
	PF	0.968	0.973	0.987	0.978	0.962
	THD	17.25	16.61	15.16	16.49	16.85
FLG	M_p	150	10	08	50	110
	T_s	0.2	0.10	0.10	0.15	0.10
	PF	0.971	0.984	0.992	0.981	0.974
	THD	13.62	12.57	11.98	12.05	13.03

4.3.1. Hardware results

The results of the simulation were verified using a hardware test. The two main forms of optimization algorithms in the modern digital age were seen as deterministic and stochastic. Optimization is widely used for addressing complicated problems. Although deterministic algorithms and stochastic algorithms, which deal with the brainchild HBO, AIS, and FLG in this drive circuit, can be easily implemented by maintaining actual dynamics as shown in Figure 8, Tables 4 and 5, the deterministic algorithm's objective function requires certain constraints or assumptions, whereas the stochastic algorithm is not confirmed. Discrete values make BLDC motor drive a complicated function for building, with the requirement of unique control strategy. While commutating currents are delayed, a decrease in resistance provides a boost to the stator's electrical time constant and steady state current. Increasing resistance results in more loss and a decrease in efficiency, it requires attention for the determination of appropriate speed management. A 2% tolerance for speed variation has been taken into consideration as per the international standards.

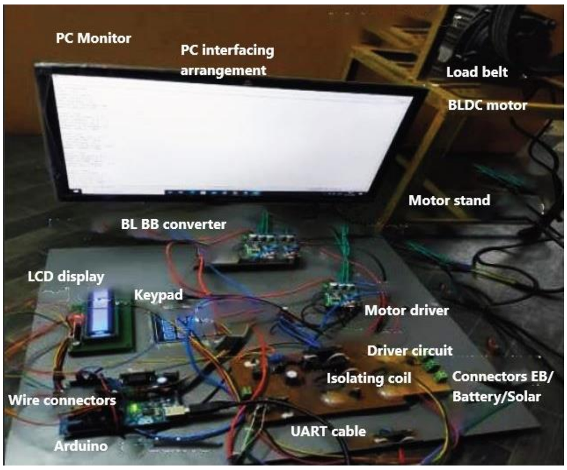

Figure 8. Snapshot of real time laboratory model hardware setup

Table 4. Hardware results @1500 RPM

Methods	Performance metrics	Loading			
		25%	50%	75%	100%
HBO	I_L	3.4	6.8	10.2	13.5
	THD	28.9	36.2	42.3	48.4
	PF	0.8912	0.8153	0.7821	0.6851
	Speed error	90	130	195	290
AIS	I_L	3.4	6.8	10.2	13.5
	THD	18.6	22.5	25.8	27.3
	PF	0.9120	0.8263	0.7912	0.7125
	Speed error	80	120	180	250
FLG	I_L	3.4	6.8	10.2	13.5
	THD	8.3	12.2	15.4	17.6
	PF	0.9812	0.9125	0.9025	0.9012
	Speed error	7	12	16	18

Table 5. Comparisons of simulated results with hardware for optimizations, Set speed=1500 rpm

Method	Performance metrics	Loading							
		25%		50%		75%		100%	
		Simln.	Hardwr.	Simln.	Hardwr.	Simln.	Hardwr.	Simln.	Hardwr.
HBO	THD	15.94	28.9	16.20	36.2	18.22	42.3	20.71	48.4
	PF	0.9364	0.8912	0.9274	0.8153	0.9210	0.7821	0.9140	0.6851
	Speed error	39.9	90	99.9	130	150	200	219.9	289.9
AIS	THD	13.28	18.6	14.30	22.5	15.70	25.8	17.25	27.3
	PF	0.9586	0.9120	0.9510	0.8263	0.9475	0.7912	0.9361	0.7125
	Speed error	19.95	79.5	90	120	109.95	180	199.95	249.9
FLG	THD	07.67	08.3	11.96	12.2	12.40	15.4	13.62	17.6
	PF	0.988	0.9812	0.980	0.9125	0.974	0.9025	0.971	0.9012
	Speed error	1.95	6.9	4.95	12	9.9	15.9	15	18

5. HARDWARE DESIGN

Coupling a motor with small value of mechanical time constant with large inertial load, shall result in losing the merit of having a small moment of inertia. Whereas, when the motor with a large moment of inertia if used for driving light load, the motor efficiency will be reduced. The most important feature of BLDC motor is its ability to balance the power converter and load requirements through electronic commutation. An experimental prototype of the proposed controller is shown in Figure 8. A bridgeless buck boost converter intended for operation in discontinuous conduction mode (DCM) either inductor current or capacitor voltage is discontinuous which is a prerequisite for the design [17] of drive circuits and in addition to that to avoid gear reducer, coupling, and pulley, power converter is activated by controller.

a. Duty ratio calculation

The motor power rating is 750 W and the converter power is 850 W. Let the supply voltage be 220 V root mean square (RMS) value, then input voltage is

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2}\times 220}{\pi} = 198\ V \tag{11}$$

$$\text{Voltage } conversion \text{ ratio}, d = \frac{V_{dc}}{V_{dc}+V_{in}} \tag{12}$$

Let the voltage limits across dc link control be

$$V_{dc(min),} = 50\ V, V_{dc\ (max)} = 200\ V$$

and $V_{dc\ (nom)} = 100\ V$ and the corresponding duty ratio d_{min}= 0.2017 and d_{max}= 0.5024 respectively.

b. Input inductors (L_1 and L_2)–design

$$L_c = \frac{R(1-d)^2}{2f_s} \tag{13}$$

L_c is calculated at d_{min} the voltage is

$V_{dc(min)} = 50\ V$ the corresponding power is 190 watts

$$L_c = \frac{V_{dc(min)}^2}{P_{min}} \times \frac{(1-d)^2}{2f_s} = \frac{50^2}{190} \times \frac{(1-0.2016)^2}{2\ x\ 20000} = 209.69\ \mu\text{H} \tag{14}$$

L_1 is taken as $\frac{Lc}{10}$,

$$\text{Hence } L_1 = L_2 = 25\ \mu H \tag{15}$$

This size, weight and cost of the buck boost converter (BBC) is reduced.

c. DC link capacitor, C_d – design

$$C_d = \frac{I_d}{2\omega\ \Delta V_{dc}} = \frac{P_o/V_{dc(nom)}}{2\omega\ \Delta V_{dc}} = \frac{850/100}{2\times 314\times 0.03\times 100} \tag{16}$$

Assuming permissible voltage ripple across the dc link voltage of

$$3\% = \Delta V_{dc} = 4511.67\ \mu F \tag{17}$$

Hence the nearest value is 5000 μF.

d. Filter circuit

A second order low pass inductance capacitance (LC) filter is applied across the supply for the elimination of negative and zero sequence components as well as higher order harmonics.

$$C_f = \frac{I_{peak}}{\omega V_{peak}} tan(\Phi) = \frac{850/220}{314\ x\ \sqrt{2}\ x\ 220} tan(1) \tag{18}$$
$$= 690.32\ nF$$

$$L_f = L_{req} + L_s \tag{19}$$

Let $L_s = 4\%$ of base impedance

$$L_f = \frac{1}{4\pi^2 fc^2 C_f} + 0.04\left(\frac{1}{\omega}\right)\left(\frac{Vs^2}{P_o}\right) \tag{20}$$

$$= \frac{1}{4\pi^2 \times 2000^2 \times 690.32 \times 10^{-2}} + \frac{0.04}{314}\left(\frac{220^2}{850}\right)$$
$$= 0.00917347032 + 0.00725365305 = 0.0164$$
$$= 16\ mH \tag{21}$$

5.1. Experimental setup

Hardware results detailed in Table 4 is compared with simulation results vide Table 5. Verification of the outcomes of the simulation for the motor parameters is mentioned in Table 6. HBO seen having lengthy search duration could get stuck in load optima details are seen in both simulation and hardware. Recognition of alien things helped the immune system, sometimes referred to as "the second brain" in the creation of self/non-self, non-linear networks from various antibodies. This can utilize the immunological law for control and eradication of antigen. Any disruption is also eliminated by the software solution, which uses digital filtering, instruction redundancy, software delay/reset and smoothing reactor/filter in hardware for the regulation of BLDC drives.

Table 6. BLDC motor parameters (for Hardware)

Parameters	Value
Number of poles	4
Power	750 Watts
Voltage	48 Volts
Current	13.5 Amp
Speed	1,500 rpm
Torque	18 Nm
Peak torque	24 Nm
Torque constant, K_T	0.86
Rotor inertia	2.5 Kg

6. CONCLUSION

The controller optimization process and controller design are critical to the tracking and controlling performance of BLDC motors. Hence proportional and integral gain values are predetermined for conventional fixed gain methods, independent of test conditions, good results cannot be obtained for all operational modes. Additionally, the outdated method does not guarantee working for one or more parameter indicators such as peak overshoot, settling time, power consumption, steady-state accuracy. The drive circuit requires the employment of many metaheuristic optimization methods, including HBO, AIS, and FLG, for the attainment of the exact speed control. Effective fine tuning for the speed control was taken as the objective for the achievement of good performance.

Frog leaping algorithm with global guided principle (FLG), a unique optimization technique is concluded as the best compared to other techniques with a minimum of 5% to 10% improvement in each performance metrics. MATLAB/Simulink 2021 software is used for creation of the fine-tuned controller and analysis of its performance under various load and speed situations. Total harmonic distortion, maximum overshoot, settling time, power factor, and other performance metrics are used for assessment of the efficiency of the controller.

Based on extensive empirical results, it is suggested that the optimization technique improves the dynamic performance of the BLDC motor under a range of operating conditions. It is verified using an Arduino controller in a real-time hardware experimental setup, closely matching simulated results, and ensuring best-in-class safety in the motion control domain. This opens up new possibilities for global optima for BLDC motor speed control.

Based on research findings it can be concluded that the proposed novel optimization technique improved the BLDC motor dynamic performance under a range of operating conditions. Thus, obtained results are validated with earlier research outcomes which are earmarked by IEEE standards. Simultaneous analysis of time domain specifications and power quality indices are suitable for aerospace applications where maintenance is not feasible.

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