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Optimized speed control with torque ripple reductions of BLDC motor based on SMC approach using LFD algorithm

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ABSTRACT

Brushless DC motors (BLDCM) are utilized in various applications, including electric cars, medical and industrial equipment, where high-efficiency speed control is necessary to meet load and tracking reference fluctuations. In this study, the optimal parameters of proportional-integral (PI) and sliding mode controller (SMC) for BLDC motor speed control are determined using Lévy flight distribution (LFD) technique. The integral time absolute error (ITAE) is used as a fitness function with the LFD algorithm for tuning the PI and SMC parameters. The optimization algorithms' performance is presented statistically and graphically. The simulation results show the SMC based on the LFD technique has superiority over SMC without optimization and PI controller in fast-tracking to the desired value with zero overshoot with rising time (6 ms) and low-speed ripple up to (± 9 RPM) under non-uniform conditions.

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1. INTRODUCTION

Brushless DC motors (BLDCM) developed a new type of DC motor in response to the rapid development of power electronic technology, control theory, and permanent magnetic materials. Its use was also more extensive than traditional motor due to several benefits, including high-precision electronic equipment, robots, aircraft, chemical mining, and many other sectors [1], [2]. For these purposes, various electric motors have been proposed [1]. There are typical DC motors, which are well-known for their high-performance characteristics. On the other hand, conventional DC motors have several drawbacks, requiring frequent maintenance brushes to be replaced regularly, and commutators must be used. The original investment [3]-[6]. Conventional DC motors are not suitable for use in a clean environment or a potentially explosive setting. The squirrel cage induction motor is a type of induction motor. An alternative to the standard DC motor, it has toughness. With a low price, its downsides, on the other hand, include a bad start, common power factor and high torque ripple [1], [7]-[9].

Furthermore, neither standard DC motors nor induction motors are suitable for this application. The application that runs at a high rate, the alternative machine to both traditional DC and AC power, is the DC brushless motor, a combination of a DC motor and an induction motor. It can be regarded as an essential electric motor in these applications. They're powered by dc voltage, but they're also powered by AC current. Solid-state switches are used for commutation. Communication of the rotor position and the location of the rotor determines instants. Position sensors or sensorless approaches detect the rotor speed or position.

The control approach must be adaptable, resilient, accurate, and easy to apply to maintain the BLDCM's stability under various conditions such as variable loads and parameters change [1], [7]-[11]. The proportional-integral–differential (PID) controller is used in multiple technical domains because of its simplicity, durability, reliability, and ease of parameter adjustment [1]. The Ziegler-Nichols rule is a well-known approach for determining PID parameters, but it is not always the best. A genetic optimization technique based on three alternative cost functions might identify the optimal PID control parameters. The main challenges that the PID control technique faces are sudden changes in setpoint and parameter variation, which causes PID control to have a poor response [4].

Advanced control techniques such as adaptive control, variable structure control, fuzzy control, and neural networks can be used to solve this challenge [4], [9], [10]. The inability to perform trajectory control in the presence of unexpected disruptions or big noises is one of the critical issues with implementing self-tuning adaptive control approaches. This is because, in the case of rapid disturbances or huge sounds, the parameter estimator may produce incorrect findings [6]. Although the variable structure controller is simple, it is challenging to practice. This is due to the risk of a sudden shift in the control signal, which could disrupt system operation [9]. The ability of a neural-network-based motor control system to address the structure uncertainty and disturbance of the system is considerable. Still, it requires more computational power and data storage space [4]. Nonlinear controllers based on fuzzy control theory can conduct various complicated nonlinear control actions, even for uncertain nonlinear systems [4]-[10]. Unlike traditional control design, an fullerene-like carbon (FLC) does not necessitate accurate knowledge of the system model, such as the system transfer function's poles and zeroes [11]. Although a fuzzy-logic control system based on an expert knowledge database requires fewer calculations, it does not have enough capacity to handle the new rules [7], [11], [12]. The sliding mode control (SMC) is used [13].

SMC is a control system that can keep a system stable in various models with different interference and system parameters. As a result, it's frequently employed in nonlinear models. SMC has a working area in the steady-state phase, which allows it to maintain system performance when disturbances and parameter changes occur. SMC based on optimization algorithm is a new system that will enable you to arrange the SMC sliding surface based on the best setting. This improves the system's transient response over the previous SMC [14], [15].

With the advancement of artificial intelligence control technology, numerous authors have been used intelligence algorithms for control of BLDCM, such as firefly algorithm [14], genetic algorithm [16], fuzzy logic control [17], neural network [18], sine-cosine algorithm (SCA) [19], particle swarm optimization (PSO) [19], moth swarm algorithm (MSA) [20], bat algorithm [21]. Bacterial foraging algorithms [22] have increasingly been added to the traditional PID controller. In this paper, to the author's knowledge, a novel algorithm is used for the first time for speed control of BLDCM for tuning the parameters of SMC, which is called Lévy flight distribution (LFD). The proposed control scheme depends on two closed-loop outer and inner loops. The outer loop is the speed control loop, and the inner loop is the current control loop. The proposed control is robust and straightforward.

2. RESEARCH METHOD

2.1. BLDC motor modelling

To analyze the dynamic response and study the behavior of the BLDC motor, a mathematical model is required. Figure 1 show the equivalent circuit of the BLD motor. According to the equivalent circuit, the differential voltage equations can be deduced in (1) [1], [2], [5], [23].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ca} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

BLDC motors typically use a surface-mounted salient-pole rotor. The winding inductance will not change with time in this situation. Furthermore, because the three-phase stator windings are symmetrical, the self-inductances and mutual inductances will be equal. The phase voltage equations of a BLDC motor can thus be represented in matrix form as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

where, $L = L_s - M$, and the developed torque equation can be expressed as below [24]-[27].

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_l \tag{3}$$

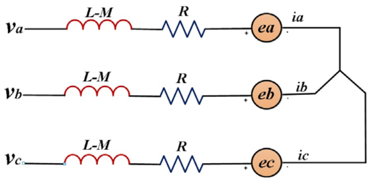

Figure 1. Equivalent circuit of the BLDC motor

2.2. Control strategy

This paper focused on comparing of the traditional techniques and optimized PI and SMC based on the Lévy flight distribution. The conventional control strategies considered in this paper are PI controller without optimized gains, PI controller with optimized gains, and SM controller without optimized gains, SM controller with optimized gains. To make a good comparison, the concept of PI and SMC are explained with modeling in [27], [28]. The algorithm is used online with the modeling of the BLDC motor during the running, and the controller error sends to the algorithm by the objective function. The proposed algorithm's control and modeling are presented in sections (3).

2.3. Proposed control structure

The proposed control strategy includes the speed control loop and the current control loop, presented in Figure 2. This paper used the SMC for the speed controller and compared it with the PI controller to track the desired trajectory. At the same time, the PI controller regulates the stator current of BLDCM. The LFD algorithm tunes the parameters of the two PI controllers to achieve excellent performance under non-uniform conditions.

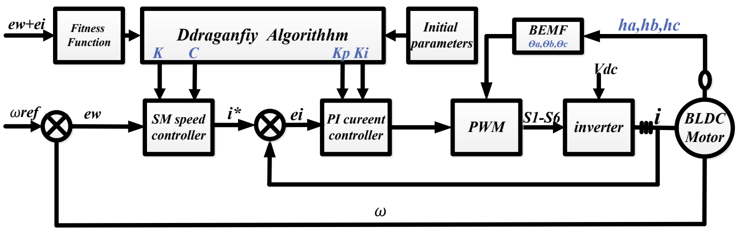

Figure 2. The structure of a BLDC motor with the proposed control approach

3. LÉVY FLIGHT DISTRIBUTION (LFD)

3.1. Inspiration

The suggested algorithm primarily focuses on the environment of wireless sensor networks combined with Lévy flight (LF) motions. As seen in Figure 3, LF can be considered a random walk. The LF shows that it can improve the efficiency of resource searches in uncertain contexts. In reality, numerous natural-inspired or physical-inspired occurrences in the environment can inspire LFs. The pathways of LF styles can be followed by natural animals such as spider monkeys, fruit flies, and humans.

Furthermore, albatross foraging practices have been discovered as an inspiration phase for the LFs. Noise and cooling behaviors indicate the features of LFs under the right conditions, and diffusion of fluorescent molecules might be considered a physically-inspired phenomenon for the inspiration of LFs. Furthermore, LFs are more efficient than Brownian random walks exploring unknown significant search areas. This efficiency is the primary justification for including LFs in the proposed optimization technique.

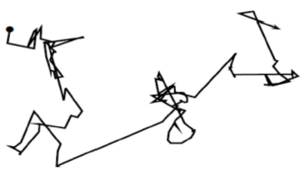

Figure 3. Lévy flights of fifty sequential steps starting from the origin marked with a bold point [29]

3.2. Mathematical model of LFD

The environment of wireless sensor networks is used for mathematical modeling. The algorithm begins its mechanism by finding the Euclidean distance (ED) between the nodes of each neighboring sensor. After that, the algorithm decides whether the node is in its original location depending on ED or moving it to another position. Another location will be calculated using LFs model in which the new location will be in a place that is close to a node with low neighboring nodes or in an area with no nodes in the search space to decrease the chances of overlapping occurring among sensor nodes.

For random walks generation, it ought to assign two characteristics: the walk length step following the selected Lévy distribution and the orientation that moves to the target location in the proposed algorithm, which may be derived from the symmetric distribution. Many procedures may determine the mentioned features, but the easiest and effective method is the Mantegna algorithm for a stable and uniform distribution [29].

Concerning Mantegna's algorithm, the step length $\mathcal{S}$ is:

$$S = \frac{U}{|V|^{1/\beta}} \tag{4}$$

where β is the index of Lévy distribution limited as $0 < \beta \leq 2$, U and V are such that

$$U \sim N(0, \sigma_u^2), \qquad V \sim N(0, \sigma_V^2)$$

the standard deviation σu and σv are:

$$\sigma_u = \left\{\frac{\Gamma(1+\beta) * \sin(\pi\beta/2)}{\Gamma[(1+\beta)/2] * \beta * 2^{(\beta-1)/2}}\right\}^{1/\beta}, \sigma_v = 1 \tag{5}$$

for an integer z the Gamma function Γ is:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt \tag{6}$$

Euclidean distance ED between the first two adjacent. Agents (and XJ) positions:

$$ED(X_i, X_J) = \sqrt{(X_i, X_J)^2 + +(y_J, Y_i)^2} \tag{7}$$

x_i, y_i is the X_i position coordinate, x_J, y_J is x_J position coordinate. ED is compared with a specified threshold till the agents are terminated after a defined iterations number. If the distance resulting is less than the threshold, the mechanism of the algorithm begins by adjusting the agent's positions using:

$$X_J(t+1) = Le'vy_{Flight(X_J(t), X_{Leader}, LB, UB)} \tag{8}$$

where t is the iteration index, the function Levy flight accomplish the Levy flights work in terms of the orientation a step length. LB and UB are the lowest and highest values in the search space 2D dimensions. X_{Leader} is the agent position with neighbors of the lowest number and will be used as the direction of the LF. in (30) moves X_J agent towards the agent's position, which has the lowest number of neighbors.

$$X_J(t+1) = LB + (UB - LB) rand(\,) \tag{9}$$

The function rand ( ) produces R random numbers in uniform distribution [0, 1]. In (31) introduce more opportunities for finding solutions of non-visited position in the search space and the suggested algorithm exploration phase increasing. In (30) updates the X_J position to a new area in the search space where no other agents are there:

$$R = rand(\,), \; CSV = 0.5 \tag{10}$$

CSV is a scalar value for comparison with R in each update for the X_J position. For updating the node X_J position, R is checked on at every iteration in (32). If R is less than CSV, execute in (30). If not, complete in (31) to give more chances to find the search space. Altering the algorithm's solutions increase its exploration capability and improve its performance. The suggested algorithm updates the X_i using:

$$X_i(t+1) = TP + \alpha_1 * TF_{Neighbours} + rand(\,) * \alpha_2 * \left(TP + \alpha_1 F_{Neighbours}/2 - X_i(t)\right) \quad (11)$$

$$X_i^{New}(t+1) = Le'vy\_Flight(X_i(t+1), TP, LB, U\,B) \quad (12)$$

New X_i is calculated by (33), while X_i final position is obtained by (34). T P is the solution achieving the objective function best fitness value, named the target position. $\alpha 1$, $\alpha 2$ and $\alpha 3$ are random numbers, and their values are such that $0 < \alpha 1, \alpha 2, \alpha 3 \leq 10$.

The total target fitness of neighbors around (t) is:

$$TF_{Neighbours} = \sum_{K=1}^{NN} \frac{D(k) * X_k}{N\,N} \quad (13)$$

where Xk is the $X_i(t)$ neighbor position, the neighbor's index is k, the total no. of $X_i(t)$ neighbors, and D(K) is the degree of fitness for each neighbor obtained by:

$$D(k) = \frac{\partial_1 (V - Min(V))}{Max(V) - Min(V)} + \partial_2 \quad (14)$$

where

$$V = \frac{Fitness(X_J(t))}{Fitness(X_i(t))}, and\ 0 < \partial_1, \partial_2 \leq 1 \quad (15)$$

All mentioned equations are repeated at every iteration. Assuming t is iterations number and n is the agents number, the LFD time complexity is (tnd), where d is each agent dimension

4. OBJECTIVE FUNCTION

This project aims to find more optimal values for PI controllers and SMC settings that control the rotor speed of the BLDC motor. A target function must create an appropriate search space and find the best PI parameters and SMC settings to solve the optimization problem. Different error parameters of the system's dynamic response can be used to describe the objective function including: i) integrated absolute error (IAE), ii) integrated squared error (ISE), iii) integrated time squared error (ITSE), and iv) integrated time absolute error (ITAE). While these definitions are accurate, we propose in this paper to use the objective function based on ITAE, which helps us to achieve better results:

$$J = min\left(\int_0^{T_{simulation}} t * [|e_w| + |e_i|\,]\,dt\right) \quad (16)$$

in (38) can describe the optimization problem in terms of the objective function: J should be as small as possible.

Where $T_{simulation}$ is the final simulation time, the problem constraints are the parameter limit of the controller; therefore, the parameters of two PI controllers are limited or SMC setting to help the optimization algorithm achieve the best parameter as fast time. So, the constrained problem design can be formulated as follows:

- For SMC

$$\left.\begin{aligned} K_{min} \leq K \leq K_{max} \\ C_{min} \leq C \leq C_{max} \end{aligned}\right\} \quad (17)$$

- For PI controller

$$\left.\begin{aligned} K_{pmin} \leq K_p \leq K_{pmax} \\ K_{imin} \leq K_i \leq K_{imax} \end{aligned}\right\} \quad (18)$$

In (39) and (40) indicates the limited values of tune PI and SMC, which are used with the LFD algorithm to tune the best parameters of the proposed controller. Figure 4 show the process of adjusting the gain values of the PI controller and the setting coefficient of SMC with the control scheme.

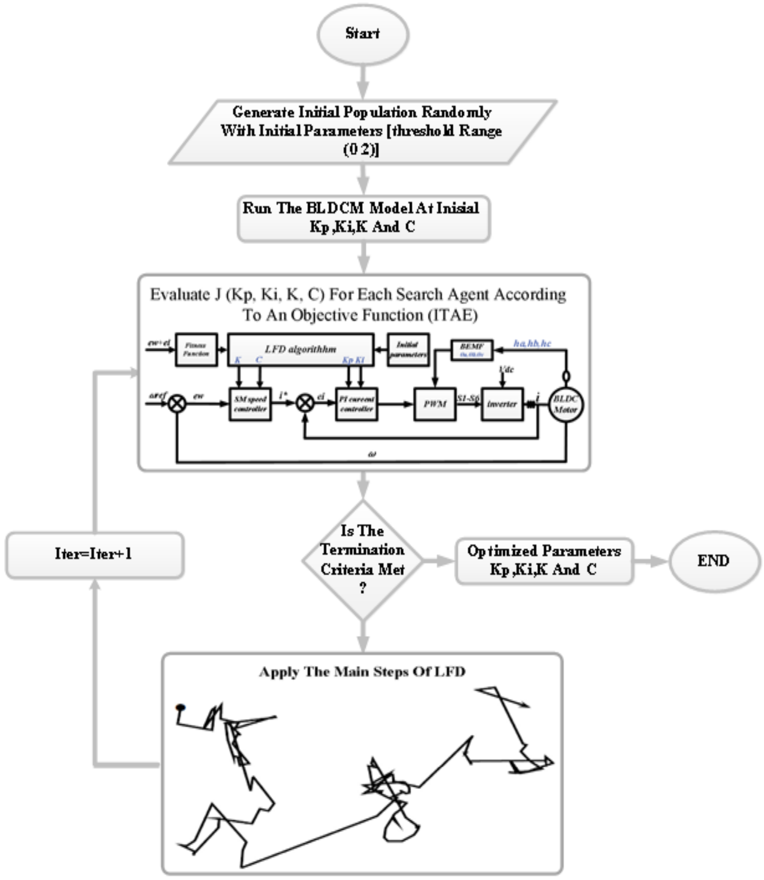

Figure 4. Flowchart of LFD for tuning the parameters of SMC and PI parameters

5. SIMULATION RESULTS AND DISCUSSIONS

This section presents the comparative performance of the proposed optimizer SMC controller with optimizer PI controller using the LFD algorithm with the same constraints (search agent=10, maximum iteration=10 and threshold value equal to 1.3) under the non-uniform conditions. Table 1 lists the parameters of the BLDC motor model utilized in the simulations. Table 2 depicts the optimum parameters of controllers using the LFD algorithm. The fitness function tracking performance for SMC and PI controller based on LFD is shown in Figure 5. It was evident from this figure the SMC with LFD has a minimum fitness value compared with PI with the LFD approach. In order to show the superiority of the proposed system, the simulation results are divided into two scenarios: dynamic response under rated conditions (w=4000 RPM and load torque 0.32 Nm) and dynamic response under non-uniform conditions.

Table 1. Specification of BLDCM Type (LVT57BL-94-001-05)

Parameters	Value	Unit
DC voltage	Vdc	36 V
Rated speed	ω	4000 RPM
Rated torque	Te	0.32 Nm
maximum current	Ia	16.5 A
Resistance	R	0.45 Ω
Inductance	L	1.4 mH
Torque constant	Kt	0.063 Nm/A
Moment inertia	J	0.0000173 Kg/m^2
Number of poles	P	4

Table 2. Parameters of controllers

Techniques	SMC		Speed controller		Current controller	
	C	K	Kp	Ki	Kp	Ki
Ziegler-Nichols	2000	5000	8	20	10	0.9
LFD	1088.941	2636.8221	0.6073	13.532	93.7725	64.102

Scenario I: Dynamic responses of BLDC motor under rated conditions. In general, the Figures 6-11 the optimization SMC has a considerably better reaction than the optimization PI control. Figure 6 shows the comparative dynamic speed response for PI, LFD-PI, SMC, and LFD-SMC. It can be seen that the speed response is based on SMC and LFD SMC is better than PI controller and LFD-PI in terms of minor steady-state error and no overshoot. Also, the chattering is mitigating with LFD-SMC as compared with SMC.

Figure 7 depicted the torque response, and we notice the SMC and LFD-SMC have notability over PI and optimum PI controller in reducing the overshoot and torque ripple. While Figure 8 shows the speed error for the four approaches, the LFD with SMC is continued as better performance in reducing error and tracking on the zero, which implies no error at the steady-state region. On the other hand, Figure 9 shows the torque-speed characteristic. We notice from this figure. The torque-speed feature quickly reached the desired value with LFD-SMC without overshoot and less ripple than PI and SMC techniques. Finally, Figures 10 and 11 demonstrated the stator currents and trapezoidal back EMF voltage under rated conditions. It can be seen that the stator current and back EMF voltage has an excellent steady state based on LFD –SMC as compared with other techniques.

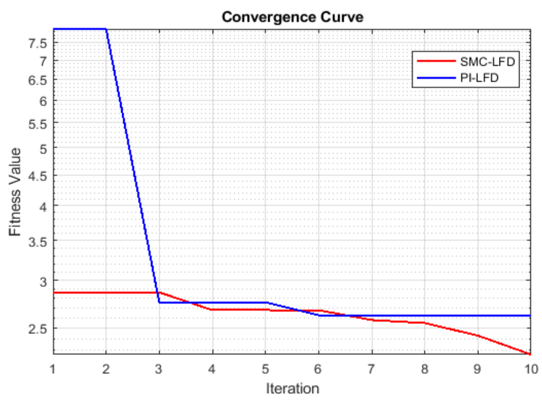

Figure 5. Fitness function of SMC and PI with LFD

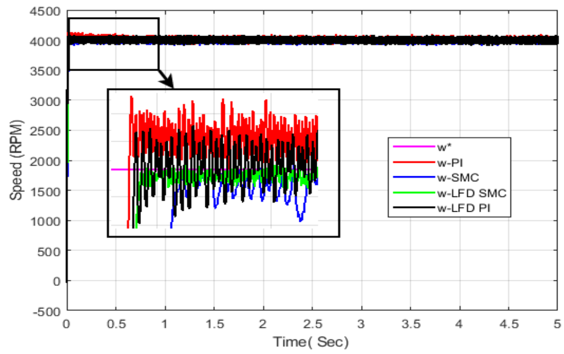

Figure 6. Speed response of BLDCM

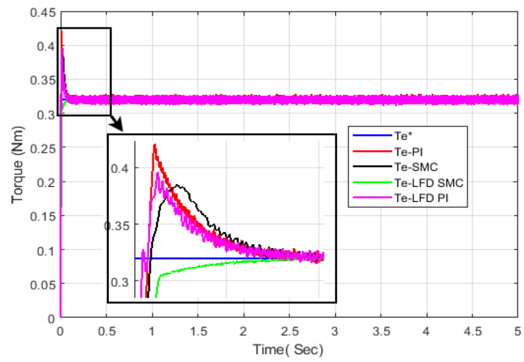

Figure 7. Torque response of BLDCM

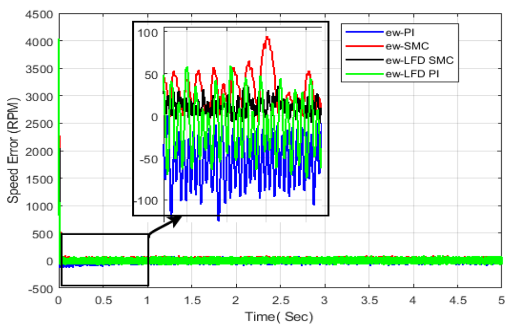

Figure 8. Speed error

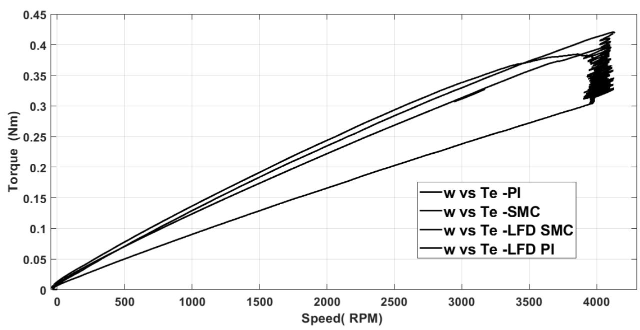

Figure 9. Torque-speed characteristic of BLDCM

Scenario II: Dynamic responses of BLDC motor under non-uniform conditions. To show the robustness of the proposed control strategy with the LFD algorithm, the proposed system is examined under various speeds and step-change loads between (0.2 Nm to 0.32 Nm at t= 1s). Figure 12 demonstrated the speed response. It is evident from this figure the actual speed is fast-tracking to desired value under variable speed. Also, the speed response with LFD-SMC has accurate trajectory tracking with no overshoot and very little chattering compared with traditional SMC.

The Figures 13, 14 and 15 have the same superiority based on LFD-SMC compared with SMC, PI, and LFD-PI controllers in terms of no steady-state error, less overshoot, and fast-tracking to the desired trajectory. While Figures 16 and 17 show that the stator current and back EMF voltage is fast change with speed and torque with very short time are reaching the steady-state without overshoot.

To provide a fair comparison between the proposed SMC based on the LFD algorithm with another traditional technique, the specification criteria are depicted in Table III. It can be evident from the results in this table that the LFD-SMC has less rise time and less settling time, which implies its fast reach to steady-state, and it has a high steady-state with no overshoot and very little ripple.

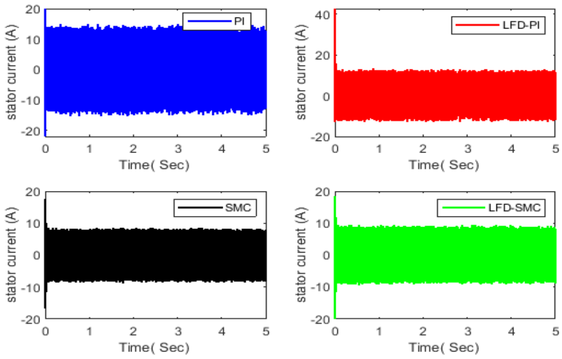

Figure 10. stator currents of BLDCM

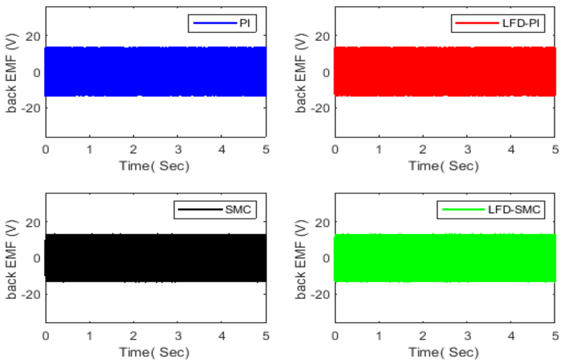

Figure 11. Back EMF response underrated

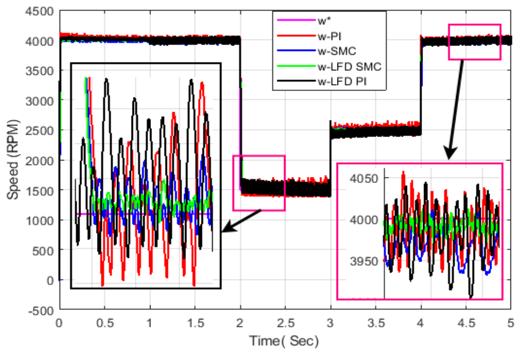

Figure 12. Speed response of BLDCM

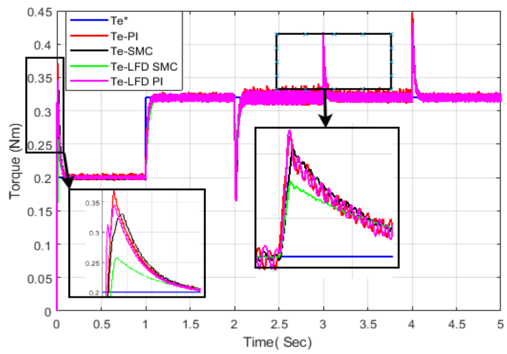

Figure 13. Torque response of BLDCM

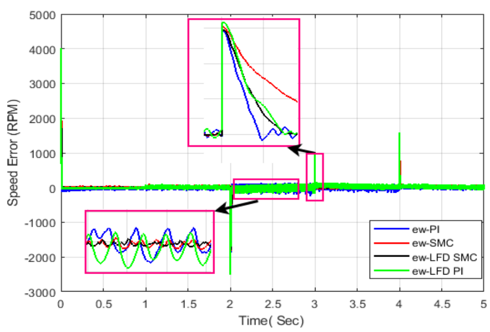

Figure 14. Speed error

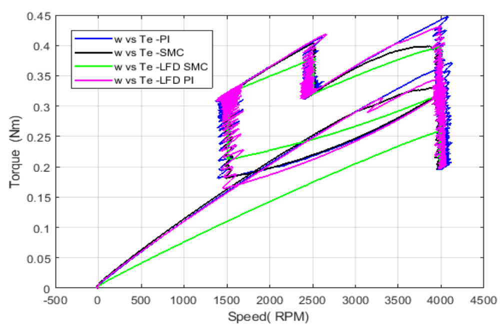

Figure 15. Torque speed characteristic of BLDCM

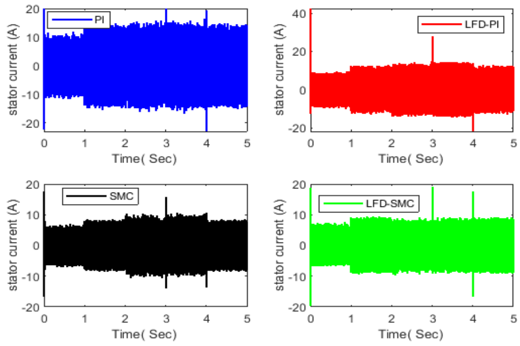

Figure 16. stator currents of BLDCM under non-uniform conditions.

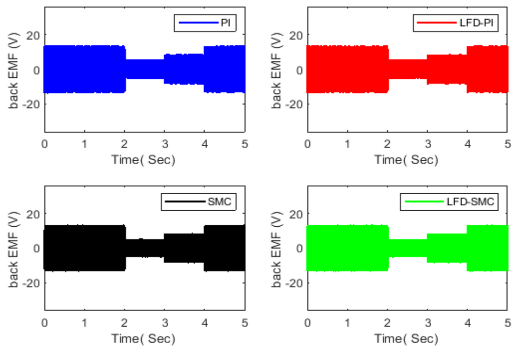

Figure 17. Back EMF response under the non-uniform condition

Table 3. Performance criteria of output speed response

Technique	ITAE	Overshoot (RPM)	Rise time	Settling time	Ripple (RPM)
LFD-PI	2.6255	78	20 ms	27 ms	± 50
LFD-SMC	2.2577	0	6 ms	8 ms	±9

6. CONCLUSION

This study uses the LFD algorithm to identify the best PI control and SMC settings. The BLDC motor speed is chosen as the system to be controlled. The ITAE is used as a fitness function based on the summation errors of comparisons between the actual speed with reference speed and reference currents with actual currents to achieve excellent tracking for speed and reduction torque ripple of BLDC motor under various conditions. The simulation results demonstrate the robust performance of the BLDC motor under variable speed and load torque compared with optimization PI and traditional SMC. These optimization algorithms for BLDC motor speed control can be enhanced in future studies by incorporating other system factors.

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