

Application of Logistic Map Methods in Adaptive Differential Evolutionary Algorithm for IoT Controlled Electronic-Vehicle Motor

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Abstract.

The new advanced and sophisticated electrical vehicle is a new technology involving many mathematical models to accommodate modern digital components. However, the most important parts of the E-Vehicles are made up of Brush Less DC motor (BLDCM). Recent developments in research studies indicated that PI controller is also very essential. The whole modeling of (BLDCM) technology is controlled by differential equations, which continue the transformation using the Laplace equation. In the same vein, all other accessories associated with the system like inverter and sensors also use the same principles. In this work, an entirely different strategy for the continuous system function was adopted without the controller gains. The feasible solution was obtained using evolutionary process of the controller. A new regulation for the speed of the BLDC motors is proposed. This LMDEA strategy involves two sequential stages that use evolutionary process and identification processes using iteration in Differential Evolutionary Algorithm (DEA). Comparative results with other approaches show convergence of crossover rate (CR) occurs with mutate factor (F). The 2-degree polynomial, non-linear equation was applied to update F, CR and different cases were compared in simulation and validated in IoT controlled hardware setup of the energetic environment.

KEYWORDS: BLDC, Differential Evolutionary Algorithm (DEA), E-Vehicles, Algorithm, LMDEA

1. INTRODUCTION

Today, robotic systems are applied in the diverse engineering capacities as one of the most effective application of both technology and science merged together. One of the most advantages of robotic application is its usage in the harsh environment where human being is considered to be too dangerous. Under this circumstance, robots controller must have the capacity to handle and control unforeseen circumstances [1]. In order to achieve this, the robot controller must be in a cascade control arrangement with the actuator controller as the final inner loops.

However, the actuator controller adaptability, flexibility and re-configurability are important for handling such task. Therefore, the brushless direct current (BLDC) motor is the most used actuator in this direction for commercial and industry applications. However, it is predicted that by the year 2030, (BLDC) motors will replace most of the traditional induction motors in the industry [2, 3]. The brushless direct current (BLDC) motor is a permanent magnet synchronous motor that is mostly used in diverse application in order to provide efficiency and control of aerospace process, submarines, electric vehicle, wind turbines, and photovoltaic energies, Unlike the permanent magnet synchronous motor (PMSM) which has sinusoidal back electromagnetic force back-EMF wave shape, the BLDC motor possess more than 42% more power density than PMSM [4]. The major difference between the PMSM and the BLDC motor is in the flux distribution in the motor, while the BLDC motor contains the permanent magnet synchronous motor with a trapezoidal back-EMF wave shape.

On the other hand, When BLDC motor is compared with brushed direct current (DC) motor; the advantages include high efficiency and reliability, long service life, high torque capabilities, low maintenance, noiseless operation, high operating speed, good dynamic response and reduction in size and weight. These are some of the advantage of BLDC motors which also come with electronic commutation circuit that replaces the mechanical commutator of brushed DC motors, hence the BLDC motors is the most widely used in electric vehicle and robots today. The

efficiency of the tracking performance of BLDC motors depends on the two main factors, the controller turning process [5] and the controller design [6, 7]. However, many proportional integral derivative (PID-like) controllers and the advanced control strategies have been adopted to address these challenges. Nevertheless, the controller design does not influence many performance characteristics such as maximum overshoot, steady-state error and energy consumption. Furthermore, the Brush Less DC motor (BLDCM) is preferred due to its simple control, which uses mathematical model originated from differential equation and progressed to attain the solution in state space model and also in Laplace transform model. The BLDCM model is expanded in next section and the control of BLDCM is the focus of this work. The PI controller is craved and tuning parameters K_{Pro} , K_{Int} are found in conventional manner especially Ziegler- Nichols methods which deals $K_{Pro}=0.45 g_m$ and $T_i=0.8 p_u$ from frequency response system. The observed system has oscillatory response and motivated to diminish the oscillatory via PI controller. Many algorithms were proposed for PI control of BLDCM and single solution called as global minimum solution, which is expected, from the search space. Here, the Differential Evolutionary Algorithm (DEA) is utilized and presented in section-III. The Internet of thing (IoT) structure is demanded in the digital era and flexible controls are promising throughout the world of modern electric car technology. The current IoT protocols are AMQP (Advanced Message Queuing Protocol), MQTT (MQ Telemetry Transport), (Constrain Application Protocol) COAP, HTTP (Hyper Text terminal Protocol), and the DDS (Data Distribution Protocol) [8] are recognized and demonstrated elsewhere [9]. Section-IV deliberated the discussion of result and ended with conclusion section.

2. SYSTEM MODEL

The permanent magnet in Brush Less DC motor (BLDCM) works based on the electronic commutation by detecting the rotor position and energizing the stator windings through the inverter. The 3-phase Y-connected stator windings are located at 120° symmetrically and motor voltage equation is articulated in matrix form as given in Eqn (1).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

The electric torque of BLDCM is given by

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \quad (2)$$

While the rotational motion of BLDCM is said to be as presented

$$T_e - T_L = J \frac{d\Omega}{dt} + B\Omega . \quad (3)$$

Where $\Omega = \frac{d\theta_m}{dt}$, and the back EMF (E_b) is given by

$$E(\theta) = f(\theta)\chi\Omega . \quad (4)$$

Here χ is flux linkage, Ω is revolving speed and while

$$\theta = \frac{P}{2} \theta_m \text{ is the electrical angle.}$$

The $f(\theta)$ provides the trapezoidal E_b and enumerated for single period given by Eqn (5) below. The TETRA 85 TR2.2 BLDCM setup is presented here and parameters are provided in Table 1.

$$f(\theta) = \begin{cases} 1 & 0 \leq \theta < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi} \left(\theta - \frac{2\pi}{3} \right) & \frac{2\pi}{3} \leq \theta < \pi \\ -1 & \pi \leq \theta < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi} \left(\theta - \frac{5\pi}{3} \right) & \frac{5\pi}{3} \leq \theta < 2\pi \end{cases} \quad (5)$$

The system is represented in state space as

$$x'(t) = Ax(t) + Bu(t) \text{ and } y(t) = Cx(t). \quad (6)$$

The state variable is also given as

$$x(t) = [I_a \ I_b \ w_r]^T \in R^3 \text{ and vector input } u(t) = [V_a \ V_b \ V_c \ T_l]^T \in R^4. \quad (7)$$

Eqn (1) is rearranged after the necessary hypothesis made where

$$A \in R^{3 \times 3}, B \in R^{3 \times 4} \text{ and } C = I \in R^{3 \times 3}.$$

$$A = \begin{bmatrix} -R/L & 0 & \chi/3L(2f_a - f_b - f_c) \\ 0 & -R/L & \chi/3L(2f_b - f_a - f_c) \\ \chi/2J(f_a - f_c) & \chi/2J(f_b - f_c) & -B_m/J \end{bmatrix}$$

$$B = \frac{1}{3L} \begin{bmatrix} 2 & -1 & -1 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & 0 & 0 & -3L/J \end{bmatrix} \quad (8)$$

The model is further diminished and the hypothesis was

$$B_m \ll 0 \text{ and } B_m R \approx B_m L \approx 0. \quad (9)$$

The current is $i_a + i_b + i_c = 0$. In operation, only two phase is active every instant and third phased current is zero,

Here $i_c=0$ and $i_a = -i_b$. Now, $x(t) = [I_a \ w_r]^T$, $u(t) = [(V_a - V_b) \ T_l]^T$ and $K_b = 2\chi$.

Therefore $x'(t) = A_{2 \times 2}x(t) + B_{2 \times 2}u(t)$ and $y(t) = C_{2 \times 2}x(t)$.

$$A = \begin{bmatrix} -\frac{R}{L} & -K_b/L \\ K_b/J & -B_m/J \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -1/J \end{bmatrix} \quad (10)$$

The system was fashioned in linear transformation given as

$$C_{2 \times 2}(sI - A_{2 \times 2})^{-1}B_{2 \times 2} \quad (11)$$

and finally established in second order nature. The transfer function (T_{fn}) is

$$\frac{\Omega(s)}{V(s)} = \frac{K_b}{(sL+R)(Js+B) + K_b^2}. \quad (12)$$

The BLDCM is operated in AC Source and well commutated in the inverter.

The $\frac{V_a(s)}{V_p(s)} = \frac{G_r}{T_r s + 1}$ is the T_{fn} of the inverter,

where G_r is the gain, T_r is time constant and the same structure for sensor with different numeric value. The inverter yield [10] depends on the pulse width, which is dictated by the PI controller, which has

$$T_{fn} \text{ of } K_{Pro} + K_{Int}/s.$$

The maximum load torque of BLDCM is 2.2 Nm and the T_{fn} is given by

$$\Omega(s)/V(s) = 0.0153/(1.183 \times 10^{-6} s^2 + 0.0005666 s + 0.009155) \tag{13}$$

The controller parameters were predicted in conventional methods and many algorithms were proposed [11-15]. The DEA procedure is used here and presented the in next section.

Table 1 represents the motor parameters

Mechanical parameters	Electrical parameters
B = 0.002125 N-m sec/rad J = 0.00018 kg-m ² K _t = 0.49 N-m/A	L = 6.57 mH R = 3.07 ohm K _p = 0.0153 V sec

3. DIFFERENTIAL EVOLUTIONARY ALGORITHM

The following procedure will be involved in DEA and adaptive factors were debated. The following relation gives the constraint of controller

$$K_{Pro_LB} \leq K_{Pro} \leq K_{Pro_UB} \text{ and } K_{Int_LB} \leq K_{Int} \leq K_{Int_UB}. \tag{14}$$

Table 2 gives the objective function of recent published work [16] and the overshoot (M_p), settling time (t_s) speed error $e(k)$ are reflected along with three weight coefficient (w_1, w_2, w_3) but the rise time (t_r) is dodged. The proposed objective function have t_r, M_p, t_s and steady state error (e_{ss}) with single modifiable value $\beta \in [0,1]$ which is also specified in Table 2.

Table 2: Objective Function

Algorithm	C	F	Objective Function
DEA[1]	0.6	0.6	$f = \sum_{k=1}^n e(k) $
MDEA[1]	0.6	$0.8 \times (1 - e^{-f(X_j)})$	$f = w_1 \sigma + w_2 t_s + w_3 \sum_{k=1}^n e(k) $
Case(i)-DEA	0.6	0.6	$f = (1 - e^{-\beta})(M_p + e_{ss}) + e^{-\beta}(t_s - t_r)$
Case(ii)-DEA	0.9	0.6	
Case(iii)-DEA	0.6	0.9	
LMDEA	$x_{n+1} = \mu x_n (1 - x_n)$		

Initialization: The initial populations (IP) are created randomly within the interval $[LB_i \ UB_i]^{pop}$

$$IP = \{(x_i \dots \dots x_\lambda)\} \text{ Where } \lambda = \text{population size } x_i = (x_{i,1} \ x_{i,2} \ \dots \ x_{i,pop})^T$$

Where $i=1,2 \dots \lambda$ and $pop=$ dimensional vector

$$x_{(i,:)} = LB_{(i)} + (UB_{(i)} - LB_{(i)}) \times rand \text{ Where } rand \in [0,1]$$

Here, the controller parameter is reflected in population and the size of population is 2.

$$IP = \{(K_{Pro} \ K_{Int})\}_{pop \times 2}$$

$$K_{Pro(i)} = (K_{Pro(i,1)}, K_{Pro(i,2)}, \dots \dots \dots K_{Pro(i,pop)})^T$$

$$K_{Int(i)} = (K_{Int(i,1)}, K_{Int(i,2)}, \dots \dots \dots K_{Int(i,pop)})^T$$

$$K_{Pro(i,1)} = K_{Pro_LB(i)} + (K_{Pro_UB(i)} - K_{Pro_LB(i)}) \times rand$$

$$K_{Int(i,2)} = K_{Int_LB(i)} + (K_{Int_UB(i)} - K_{Int_LB(i)}) \times rand$$

Mutation: The mutation operations are treated now for each individual of x_i and mutant vector $v_{(i)} = (v_{(i,1)}, v_{(i,2)} \dots \dots v_{(i,n)})$ is formed by

$$v_{(i)} = x_{(g1)} + F (x_{(g2)} - x_{(g3)}).$$

The $x_{(g1)}, x_{(g2)}, x_{(g3)}$ are dissimilar individuals randomly selected from $x_{(i)}$.

The $F \in [0,2]$ is amplification factor and suggested as $F = 0.6$ [17]. The $v_{(i)}$ should be with-in the interval bounds and iterate the process, if $v_{(i)}$ exist beyond the interval limits.

For controller, $v_{(i)} = (v_{(K_{Pro(i)})}, v_{(K_{Int(i)})})$

$$v_{(K_{Pro,1})} = (K_{Pro(g1,1)} + F (K_{Pro(g2,1)} - K_{Pro(g3,1)}))$$

$$v_{(K_{Int,1})} = (K_{Int(g1,2)} + F (K_{Int(g2,2)} - K_{Int(g3,2)}) \text{ Where } g1 \neq g2 \neq g3$$

Cross over: The cross over rate ($CR \in [0,1]$) is applied to produce the trial vector $u_{(i)} = (u_{(i,1)}, u_{(i,2)} \dots \dots u_{(i,n)})$ which is formed from target vector x_i and mutate $v_{(i)}$

$$u_{i,j} = \begin{cases} v_{i,j} & \text{if } rand \leq CR \\ x_{i,j} & \text{otherwise} \end{cases}$$

For controller, $u_{(i)} = (u_{(K_{Pro(i)})}, u_{(K_{Int(i)})})$

$$u_{(K_{Pro(i,1)})} = \begin{cases} v_{K_{Pro(i,1)}} & \text{if } rand \leq CR \\ K_{Pro(i,1)} & \text{otherwise} \end{cases}$$

$$u_{(K_{Int(i,1)})} = \begin{cases} v_{K_{Int(i,1)}} & \text{if } rand \leq CR \\ K_{Int(i,1)} & \text{otherwise} \end{cases}$$

The CR is fixed in DEA and suggested value is $CR = 0.6$ [18]. The trialed CR and F value are given Table 2 and the precise values leads to the fast convergence in solution. These values are changed in every iteration therefore called as adaptive DEA. Here, polynomial of degree two known as logistic map is proposed. The logistic map is non-linear equation and expressed as $x_{n+1} = \mu x_n (1 - x_n)$. The range of parameter μ is (0 4) and produces a two effects namely (i) reproduction which increases population based on present population and (ii) starvation where the growth rate of population decreases. The bifurcation diagram of logistic map is shown in Fig.1 and the observations are

- (i) During $\mu=0$ to $\mu=1$, the population will die irrespective of original condition.
- (ii) During $\mu=1$ to $\mu=3$, the population will linearly increases at the rate $\frac{\mu-1}{\mu}$ and at $\mu=3$ fluctuate start
- (iii) After $\mu=3$, the population will have permanent oscillations and beyond $\mu=4$, almost all original values leave the interval and diverge. So $\mu=4$ is designated and the adaptive parameters of CR and F is expressed in nonlinear equation given in Eqn(14) and Eqn(15).

$$CR_{i+1} = \mu CR_i (1 - CR_i) \tag{14}$$

$$F_{i+1} = \mu F_i(1 - F_i). \tag{15}$$

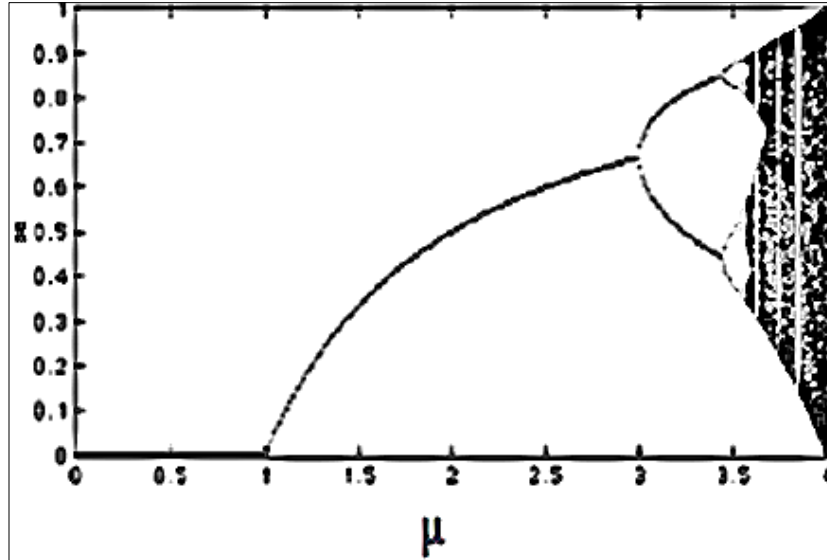


Fig.1. Logistic Map

Fitness function: Now, the next set of parent is made from above process and implemented based on fitness value (*fit*). The *fit* is calculated for each individual and best-fit yield offspring set is used as parent for next generation.

$$x_{next_gen} = \begin{cases} u_{i,j} & \text{fit}(u_{i,j}) < \text{fit}(x_{(i)}) \\ x_{i,:} & \text{fit}(u_{i,j}) \geq \text{fit}(x_{(i)}) \end{cases}$$

For controller,

$$x_{Next_gen} = \begin{cases} u_i & \text{fit}(u_{(i)}) < \text{fit}(x_{(i)}) \\ IP_i & \text{fit}(u_{(i)}) \geq \text{fit}(x_{(i)}) \end{cases}$$

The mutation, crossover and fitness function steps are repeated until fulfill the stopping criteria. The iterations are preceded to select the best controller parameters and minimum error is selected after the maximum iteration (50th iteration).

4. RESULTS AND DISCUSSION

The entire system model was implemented in MATLAB environment and it has 4-pole, 1-zero without controller. The performance were witnessed in time domain specifications:

$$\begin{aligned} Tr &= 0.2527 \text{ sec} \\ Ts &= 0.2809 \text{ sec and} \\ Mp &= 14.9928\% \end{aligned}$$

For unit step input and frequency domain specifications:

$$\begin{aligned} \text{Gain cross over frequency} &= 176 \text{ rad/sec,} \\ \text{Phase margin} &= -6.04 \text{ deg,} \\ \text{Phase cross over frequency} &= 120 \text{ rad/sec,} \end{aligned}$$

Gain margin = -4.78db.

The system have overshoot, oscillatory response and it will be reduced to least value by adding the controller. The range of controller was $0 \leq K_{Pro} \leq 1$ and $0 \leq K_{Int} \leq 37$ for the real time implementation. The parameters $K_{Pro} = 0.014$ and $K_{Int} = 17.61$ was found in conventional method via tuning rule. In DE, The standard procedure was pursued for 50 iteration and found K_{Pro} and K_{Int} values. The expected solution acquired from iteration process also depends upon CR, F and the contribution of different values of CR, F was evaluated and presented in Table 3. The solution given in [13] where valve CR=F=0.6 are used and error plot is given Fig.2. The tentative solution was obtained in 30th iteration and observed the quick response (I the 20th iteration) as F increases (F=0.9). When CR=0.9 and F=0.6, the possible solution was obtained in 47th iteration which is almost near to the maximum iteration which was not included. We obtain values for CR=0.6, F=0.9 with standard DEA. The CR and F were changed in all iteration, which provides the quick response. Therefore, adaptive nature of CR and F was initiated and especially (Levenberg-Marquardt Differential Evolutionary Algorithm)) LMDEA was proposed. The LMDEA produces fast convergence of the expected output in the iterative process with least error for CR=0.712, F=0.825 through the logistic map. The Fig.3 shows the applied load torque and Table 4 shows the valeted result in hardware.

Table 3 Comparisons of Controller Parameters in DEA and LMDEA

Algorithm	C	F	K_{Pro}	K_{Int}	Maximum iteration	Best solution in iteration
Case(i)-DEA	0.7	0.7	0.8309	6.5863	60	30
Case(ii)-DEA	0.8	0.7	0.6964	8.4836		45
Case(iii)-DEA	0.7	0.8	0.7408	6.6827		17
LMDEA	0.712	0.325	0.7667	6.3297		8

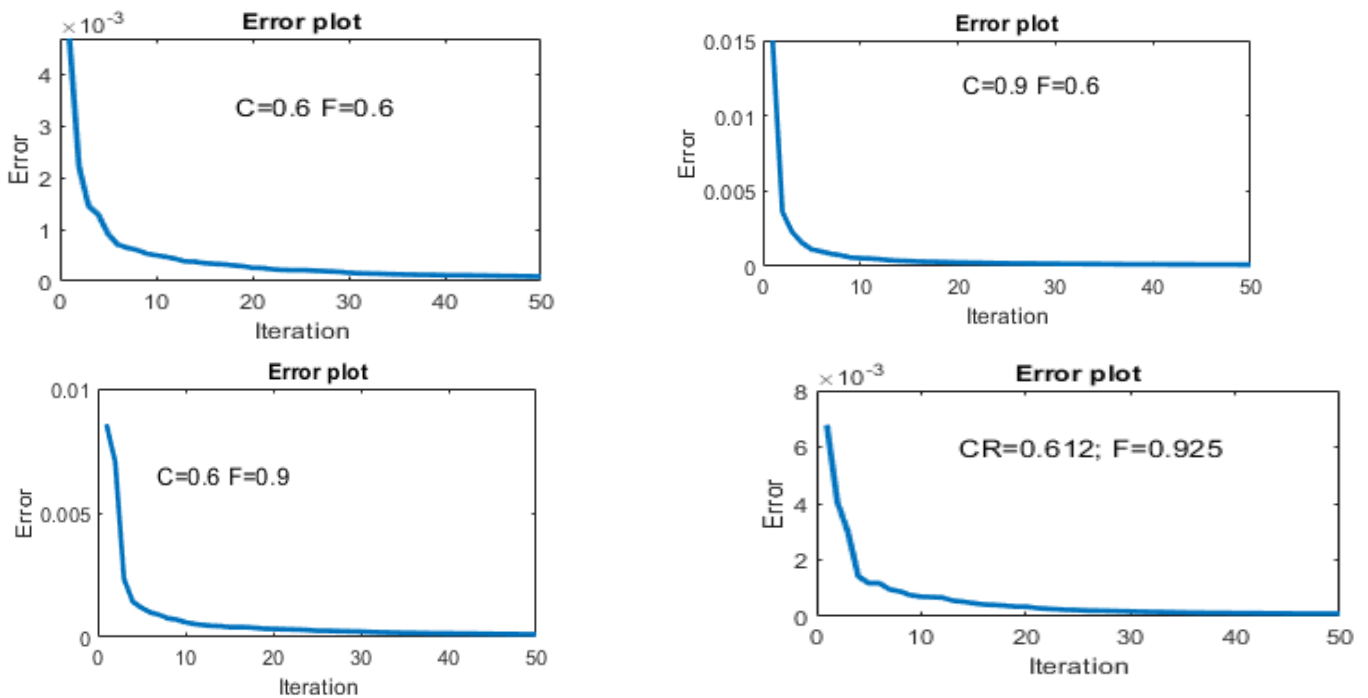


Fig.2. Demonstrating Error plot for different CR and F values

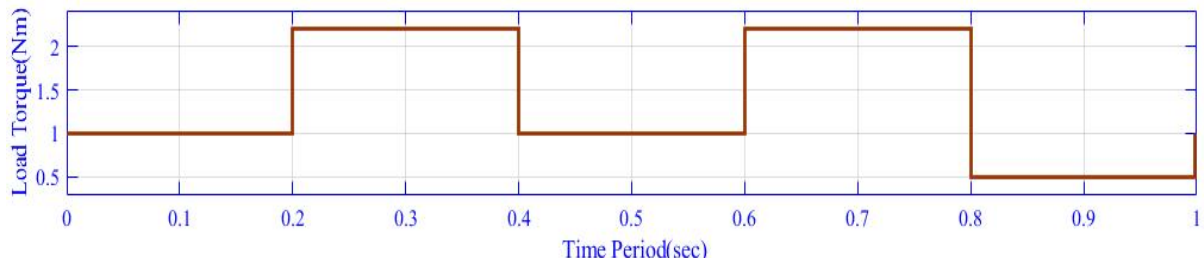


Fig.3. Shows the Applied load Torque

Table 3 demonstrates several progresses in comparisons between DEA and LMDEA for speed controller brushless BLDC motor. The result indicated that most of the algorithm applications depend on the genetic algorithm (GA) and particle swarm optimization (PSO). The inclusion of other dynamics in metaheuristics as presented in [19] demonstrates the impact of the functions rather than classic pseudo-random functions. Nonetheless, DEA dynamics presence in the controller turning task for BLDC motors has not been so far reported anywhere in the literature. However, the most important result of this work is the use of the Levenberg-Marquardt Differential Evolutionary Algorithm (LMDEA) in an online process to appropriately stabilize its search capabilities by maintaining the motor velocity error-free under the effect of disturbances.

Table 4 outlines the experimental results for PI, DEA, and LMDEA showcasing their operating conditions. This table includes the type of controller, percentage error, time in sec, minimum and maximum speed, and load torque for each case of the controller, and the best results are identified. Using the above values, the proposed LMEDA showcases the best-performing alternative for BLDC brushless motor, which utilizes Differential Equation as the stabilizer. On the other hand, DEA is not also far away from the other controllers, while the PI provide the worst results. However, all strategies incur a small increase in error under the strategy. This highlights the ability for the approach to handle uncertainties, perturbation, and noise.

In the error graphs of Figure 2 there are no visible differences between the best and worst outputs for both strategies. In the case of PI and EDA, some error peaks stand out from the inner plots in comparison with the error signals of LMDEA. In the case of LMDEA approach, the peak-to-peak error seems more attenuated than in the rest of the alternatives. Still, it has very high peaks and is always above the reference for both operating conditions. On the other hand, the control action in Figure 3 reveals that control strategies require much more energy to compensate for the difficulties of applied load torque. Considering the error of the speed regulation task, the excellent performances of the LMDEA controller based are clearly attributed to marginal balance of abilities for exploration and exploitation.

Table 4. Experimental Results of PI, DEA and LMDEA

Types of Controller	PI					Case(iii)-DEA					LMDEA					
Controller Parameter	$K_{Pro} = 0.013$ $K_{Int}=16.61$					$K_{Pro}= 0.6408$ $K_{Int}=5.6827$					$K_{Pro} =0.6667$ $K_{Int}=5.3297$					
Time Period(sec)	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	
Load Torque (Nm)	1	2.2	1	2.2	0.5	1	2.2	1	2.2	0.5	1	2.2	1	2.2	0.5	
Maximum Speed(rpm)	1998	2020	2090	2008	2115	1998	2001	2050	2003	2030	2100	2003	2004	2003	2008	
Minimum Speed(rpm)	1890	1900	1992	1940	2008	1993	1949	2000	1953	1980	1800	2000	2001	2000	2000	
Error during load changes (rpm)	1100	-102	80	-81	109	600	-50	50	-50	80	300	3				
Percentages of Error during load changes	55	-5.1	4	-4.1	5.45	30	-2.5	2.5	-2.5	4	15	0.15				
Recovery time during load changes (sec)	0.19	0.13	0.1	0.08	0.14	0.023	0.03	0.026	0.03	0.034	0.015	0.001				
Jerk at load changes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	
Smoothness of operation	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	
Oscillation during steady state	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	
Execution Time	Low					Low					High					
Stable	Yes					Yes					Yes					
Memory size	Low					Low					High					
Cost	Low					Low					High					

Complexity	Low	Low	High
Reliability	Less	Less	More

5. CONCLUSION

The mathematical model of BLDCM and its associated parts of E-vehicle was established with the support of a differential equation, and the Laplace equation. The obtained results indicate that the control part called PI controller parameters identification with conventional approaches originated from the 4-pole, 1-zero system. The controller parameter was also identified in DEA with different F and CR and these values bring to adaptive nature by incorporating a logistic map with DEA. The elucidations of oscillatory response are reduced and the feasible solution was developed in a short span of iteration as compared with another controller. The LMDEA was prepared for real-time implementation and validated in the Internet of Things (IoT) based hardware setup. The parametric test authenticates the reliability of the approach. Future work should include the experimental verification of the proposed LMDEA and the implementation of the LMDEA approach in a more complex system. The convergence period is an important factor in the approach and therefore joining a lookup table for parameters according to the system operating condition will help in the analysis of disturbance and uncertainties of the entire system.

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