PERFORMANCE ENHANCEMENT OF DIRECT TORQUE CONTROLLED BRUSHLESS DC MOTOR USING SOFT COMPUTING METHODS

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Abstract: *The BLDC motor speed control is creating more importance in industry as it is used in many applications now-a-days. In order to get the accurate and reliable control action Direct Torque Control method is used and PI controller is used to generate the reference signal. The conventional methods of tuning the parameters Kp and Ki is based on trial and error which consumes more time. Hence, in this paper intelligent technique such as Fuzzy logic, Particle Swarm Optimization (PSO) and Cuckoo Search Algorithm (CSA) are proposed to tune the parameters of PI control algorithm. The transient performance and efficiency of the BLDC motor is analyzed to determine the stable and efficient operation. CSA tuned PI control algorithm yielded better performance compared to PI, Fuzzy and PSO tuned PI control algorithms.*

Keywords: *Cuckoo Search Algorithm, Particle Swarm Optimization,Fuzzy Logic, Brushless DC Motor.*

1.Introduction

Brushless DC motors (BLDC) are widely used in variety of applications such as constant loads, varying loads and positioning applications in automation systems, industrial control, aviation, automotive, health care equipments, etc. Brushless DC motors do not have brushes and are electronically commutated, and overcome the disadvantages of conventional DC machines like the need of mechanical brushes and the associated commutation problems which made this type of motors are inevitable for high performance applications. The machines with electronic commutation have large scope of capabilities and flexibility. The significant characteristics of Brushless DC motors are Smooth operation and holding torque when stationary. The applications of BLDC motors need precise position control, the importance of accurate control with fast response becomes mandatory and vital. Also, these applications necessitate the torque speed characteristics to be superior and load density to be low.

Generally, current control method is employed in BLDC drives where the torque is proportional to the phase current. But in practical cases, the relationship between torque and current is nonlinear in nature. Hence, various current control strategies have been proposed for minimization of torque pulsations with pre-optimized waveforms as the reference current. Sung P J et al. (2000) proposed a scheme with optimal current excitation based on the axes transformation. Minimal copper loss, ripple-free torque and no response to rapid torque changes in the BLDC drive are the advantages of this method. In order to reduce the torque ripples, many other methods have also been proposed in the literature such as estimation of electromagnetic torque from the rate of change of coenergy (French & Acarnley, 1996), an instantaneous torque controller with variable control structure in the reference frame (Low et al. 2000), torque estimation by the product of the instantaneous back-EMF and current (Kang et al. 1995). These methods are not involving flux and applicable to certain mode of operations only. As the operating principle of the motor involves the flux, methods need to be formulated involving flux for accurate control. Direct Torque Control (DTC) method has been suggested in which decoupling of current into two components responsible for torque and flux and accurate control is achieved.

In DTC of PMBLDC, the motor is fed from both the inverter and connected supply and the motor is operated either in flux priority or torque priority modes and two-control topology is used for analysis. The two-control topology is used because under steady state operation, the PMBLDC motor sometimes goes to an unstable state where it could not be controlled either by the torque control or by the flux control (Izaskun Sarasola, 2011). In Direct Torque Control, there is a possibility of controlling the stator flux and the electromagnetic torque by the application of suitable combinations of the control signals to the inverter switches. The direct torque control of The BLDC motor with direct torque control is fed through four switch inverter topology instead of conventionally used six switch inverter. The four switch inverter topology can be obtained from the reconfiguration of six switch inverter in case of a switch/leg failure. Electric and hybrid propulsion systems are the applications of this configuration (Mourad Masmoudi, 2013).

In DTC, the estimated flux magnitude and torque are compared with their reference values. PI controlled speed regulator is used to generate the reference torque because of its simple control structure and easiness in design. The parameters of PI parameters need to be tuned to avoid the torque disturbances at low speeds and improve the performance of the system at all the range of speed. However tuning the parameters of PI controller is a difficult task. The Conventional methods of tuning are based on trial and they are not able to use in hazardous situation. Hence, the scientist and researchers moved to use different soft computing techniques like Fuzzy Logic, Genetic Algorithm (GA), Particle swarm optimization (PSO), Cukoo Search Algorithm (CSA), etc to enhance the capabilities of traditional PI parameter tuning techniques. In this paper, the analysis on transient performance of direct torque control of PMBLDC motor is made by using fuzzy tuned PI, PSO tuned PI and Cuckoo Search Algorithm (CSA) tuned PI controllers. The simulation results of BLDC drive employing the above controllers are compared and evaluated under various load disturbances in the MATLAB/simulink environment.

2. DIRECT TORQUE CONTROL OF PMBLDC MOTOR

As the BLDC motors are most suited for high precision applications like the electric vehicles and aerospace applications, it needs accurate speed control with lesser loss which is of prime importance. DTC method is used to obtain the high precision speed control with lesser loss. The mathematical model of the PMBLDC used to implement the control algorithm motor is derived as follows.

The control algorithm for DTC is developed by considering the direct and quadrature axis reactances of the motor. Neglecting the influence of mutual coupling between direct and quadrature axis, the expression for electromagnetic torque is given in equation (1) (Yong Liu, 2005).

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\left[\left(\frac{dL_d}{d\theta_e}\right)i_{sd} + \left(\frac{d\psi_{rd}}{d\theta_e}\right)i_{sd} - \psi_{sq}\right]i_{sd} + \right\} \left\{\left[\left(\frac{dL_q}{d\theta_e}\right)i_{sq} + \left(\frac{d\psi_{rq}}{d\theta_e}\right)i_{sd} - \psi_{sd}\right]i_{sq}\right\} \quad (1)$$

Where, T_e is the electromagnetic torque developed, P is the number of poles, L_d and L_q is the direct and quadrature axis self inductances, θ_e is the electrical angle of the rotation, ψ_{sq} and ψ_{sd} are the quadrature and direct axis flux linkages in stator, ψ_{rq} and ψ_{rd} are the quadrature and direct axis flux linkages in rotor, i_{sq} quadrature axis stator current and i_{sd} the direct axis stator current.

$$\psi_{sd} = L_d i_{sd} + \psi_{rd} \quad (2)$$

$$\psi_{sq} = L_q i_{sq} + \psi_{rq} \quad (3)$$

The values of ψ_{sq} and ψ_{sd} from equations (2) and (3) are considered and incorporated in equation (1), the torque equation for BLDC motor can be simplified as equation (4).

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \quad (4)$$

The simplified torque equation in alpha-beta coordinate is

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{s\alpha} i_{sb} - \psi_{sb} i_{s\alpha}\right) \quad (5)$$

obtained as in equation (5).

Where, $\psi_{s\alpha}$ and ψ_{sb} are flux linkages in alpha and beta coordinates, $i_{s\alpha}$ and i_{sb} are stator currents in alpha and beta coordinates.

From the mathematical model, the block diagram for the direct torque control of PMBLDC motor is developed and is shown in Figure 1.

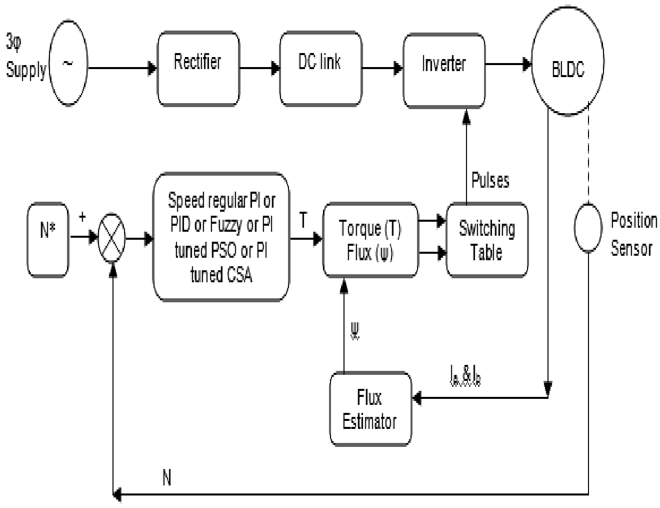


Figure 1 Block diagram of the proposed work

The switching sequence of the windings of the motor in drive system determines the controlled operation of BLDC motor and is given in Table 1. The corresponding Vector Values (‘V’s) are given in Table 2. The vector values ‘1’s and ‘0’s in the vector table represent the ‘ON’ and ‘OFF’ conditions of the switches.

Table 1 Switching Table

Torque (T)	Flux	Sector					
		I	II	III	IV	V	VI
1	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_3	V_4	V_5	V_6	V_1	V_2
0	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_0	V_0	V_0	V_0	V_0	V_0
	-1	V_3	V_4	V_5	V_6	V_1	V_2

Table 2 Vector Table

V0	000000
V1	100001
V2	001001
V3	011000
V4	010010
V5	000110
V6	100100

3. CONVENTIONAL SPEED REGULATOR

PI and PID are the mostly used conventional controllers in speed regulation of electrical drives. The error in speed $e(t)$ = N*-N is calculated. Where, N* is reference speed and N is the actual speed which is measured through position sensor; and the error should be minimized by the controllers to get the better speed regulation. The output of the controller is represented as $Out(t)$. The output of the conventional PI speed regulator is expressed in equation (6).

$$Out(t) = K_p e(t) + K_i \int e(t)dt \quad (6)$$

Where, K_p is the proportional constant and K_i is the integral constant which determine the output of the speed regulator as per the error signal.

Similarly with additional derivative term (K_d) in equation (6), the output of the PID controller can be represented as in equation (7).

$$Out(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (7)$$

The controller gains K_p, K_i and K_d in equation (7) are tuned using conventional trial and error methods. These methods are time consuming and the accuracy of the results is not also encouraging. Therefore, soft computing methods are used to determine the optimal values of K_p, K_i and K_d to get the optimal error value in speed. Particle Swarm Optimization method and Cuckoo Search Algorithm are used to optimize the gains. The objective function used in these techniques is given below.

As per the literature and in practical, the PI controllers are preferred to improve the transient performance of electrical drives. The variation in speed characteristics are the outcome of the random variation of PI controller parameters with fixed limits. There are infinite numbers of possibilities to choose the parameters of PI controller through trial and error. Hence, it should be restricted to limited number by choosing the objective function with constraints. The optimal values of parameters K_p and K_i are found with the objective of minimization of steady state error.

Vectors	Values
V_0	000000
V_1	100001
V_2	001001
V_3	011000
V_4	010010
V_5	000110
V_6	100100

Therefore, the optimal parameters in equation (6) are determined using PSO and CSA algorithms as per the objective function and constraints defined in equations (8) and (9) respectively.

Minimization of steady state error $\sum_{i=1}^{n}(N^* - N)$ (8)

With respect to constraints

$$K_{p\min} \le K_p \le K_{p\max}$$
$$K_{i\min} \le K_i \le K_{i\max} \quad (9)$$

Where, $K_{p\min}$ and $K_{p\max}$ are the minimum and the maximum values of proportional gains, while $K_{i\min}$ and $K_{i\max}$ are the minimum and maximum values of Integral gains, and are obtained by the experience while PI controller is used

4. FUZZY BASED SPEED REGULATOR

The algorithm of Fuzzy logic control (FLC) is developed based on linguistic control strategy by accounting the human's knowledge and expertise. In fuzzy logic, If-Then rules are the main part of the controller and therefore, it is called as rule based system. The fuzzy logic control is mostly preferred to the system which is highly non-linear in nature and no mathematical modeling is available. The basic structure of this approach consists of fuzzification, knowledge base, rule base, inference engine and defuzzification processes. The linguistic terms are used in Fuzzy logic in place of numerical variables as in real time system. The process of converting a numerical variable (real number or crisp variables) into a linguistic variable (fuzzy number) is called Fuzzification.

The input and output variables used in the design of fuzzy logic based speed regulator of BLDC motor are the error in speed (E) and change in speed error (CE), and torque respectively. The error in speed is calculated by comparing the reference speed and actual Speed. Adaptiveness is the significant characteristic of fuzzy logic controller. Even though there are uncertainty in parameters variation and disturbance in load, fuzzy logic controller produces robust performance in the system because of its adaptiveness characteristics. The fuzzy logic controller is used to produce an adaptive control so that the motor speed can accurately track the reference speed. Formation of IF-THEN statements is the major part of design of a fuzzy logic controller, where the IF part is called the "antecedent" and the THEN part is called the "consequent". In the design of present work, five linguistic terms such as Negative Big (NB), Negative Medium (NM), Zero(Z), Positive Medium (PM) and Positive Big (PB) are used for both the input and output variables; and triangular membership functions used. A total of 25 rules have been formed in the present design.

5. PARTICLE SWARM OPTIMIZATION

The principle of Particle Swarm Optimization (PSO) algorithm is based on the principle idea of social behaviour of animals for searching the food through shortest route to reach the place of food available which was introduced in the year 1995 by Dr. James Kennedy and Dr. Russell Eberhart. Particularly, it was developed based on the social behaviour of animals such as bird flocking, fish schooling and so on. It is based on the natural process of group communication to share individual knowledge when a group of birds search for food in a searching space, even though they do not know where the food is available and the shortest route to reach the place of food available. But due to the nature of the social behaviour, if any member of any group of animals finds the desirable path to go, the rest of the members will follow quickly.

In PSO, food available area is the search space, the swarm is considered as the population and each member in the particular group of animal's population is considered as the particle. All particles are initiated and allowed to move in the chosen directions randomly. Each particle goes through the searching space to find the individual best (best position of each particle) and the position which is the lowest value amongst best of all the individuals is called as global best (best position of particle in the entire swarm). The velocity of particles is updated based on individual and global best positions, and then the positions of each particle are updated as per present velocity. A stopping criterion is used to end the loop updation of velocity and is predetermined in advance. In summary, in PSO algorithm food is the objective function, the particles are the population and swarm is the total population in every iteration. The procedural steps of PSO algorithm are described as given below

Step 1 Make assumption on the size of the swarm or particle (N) and choose the size as 20 to 30 particles

Step 2 Create the initial population of X in the range X(l) and X(u) randomly and are represented as $X_1, X_2, \ldots X_N$.
Step 3 Formulate the objective function and Evaluate its value.
Step 4 Assume zero to all initial velocities. Determine the velocities of particles. All
particles move towards the optimal point.

Step 5 Find initially, the historical best value of the particles, which is known as local best, or particle best (Pbest) and find the best particles of all the previous iterations called as global best or Gbest. The Individual and Global best positions are updated for the next iteration as per equations (10) and (11) respectively.

$$P_{best\ i}^{itr+1} = \begin{cases} P_{best\ i}^{itr} & \text{if } f(x_i^{itr+1}) > P_{best\ i}^{itr} \\ x_i^{itr+1} & \text{if } f(x_i^{itr+1}) \le P_{best\ i}^{itr} \end{cases} \tag{10}$$

$$G_{best}^{itr} = \min\left\{ P_{best\ i}^{itr} \right\} \tag{11}$$

Velocity and positions of particle are updated for the $(itr+1)^{th}$ iteration by using equations (12) and (13) respectively.

$$v_i^{itr+1} = v_i^{itr} + c_1 r_1^{itr} [P_{best\ i}^{itr} - x_i^{itr}] + c_2 r_2^{itr} [G_{best}^{itr} - x_i^{itr}] \tag{12}$$

$$x_i^{itr+1} = x_i^{itr} + v_i^{itr+1} \tag{13}$$

where,

v_i^{itr} – Velocity of particle i at iteration itr.

x_i^{itr} – Position of particle i at iteration itr.

$P_{best\ i}^{itr}$ – Individual best position of particle i at iteration itr.

G_{best}^{itr} – Global best position at iteration itr.

c_1 and c_2 – Cognitive and Social parameters respectively.

r_1^{itr} and r_2^{itr} – Random numbers in between 0 and 1 at iteration itr.

Step 6 Check the convergence of the current solution, if the positions of all particles. Reach the convergence stop the iteration else increment the iteration number and evaluate step 5.

6. CUCKOO SEARCH ALGORITHM

Cuckoo Search Algorithm (CSA) is the new optimization algorithm based on the social behavior of the Cuckoo bird and fruit fly. Cuckoo Birds which are mostly found in Europe, Asia and Africa. During winter season, they start to breeding and have many interesting features in breeding. Aniand Guira is one of the types of Cuckoo birds and has the habit of laying eggs in common nest. Usually, Cuckoo chooses a guest nest to lay its eggs. The main significant features of the Cuckoo eggs are looks like the eggs of host birds and hatch fast compared to the eggs of host. After laying the eggs, the host birds move from the nest and build a new nest and there it lays eggs. If it stays in the nest, it randomly pushes the eggs from the nest. The most number of cuckoo birds survives in the host nest at last is treated as the best nest for the parent cuckoo. Like Cuckoo birds, the chicks of Cuckoo also capable of making the mimicry like the host chicks to get the maximum food from the host bird. The relevant optimization algorithm has been built by obtaining the mathematical modeling based on the concept of behavior of Levy Flights. It is used in the random walk of a variable for choosing the random nests. In order to implement the algorithm in a simplified way, the following assumptions are made (Zhang & Wang, 2011)

- Each Cuckoo lay only one egg at a time and dumps it in randomly chosen nests
- The nests with high quality of eggs is treated as best nest and carried over to the next generation
- The number of host nest is fixed and the probability of host bird to identify the eggs laid by a cuckoo is in between 0 and 1

In this algorithm, the solution is represented by each egg in a nest and the new solution is represented by cuckoo egg. Cuckoo birds via levy flights algorithm has proven that it gives better results compared to other meta-heuristic optimization algorithms such as PSO and GA. The procedure for CSA algorithm is given below.

Step 1 Initialize "n", the number of host nests where X_i (i= 1, 2,..n) and maximum number of iteration.
Step 2 Randomly choose a cuckoo by levy flights and evaluate the fitness function (F_i) for every iteration before reaching the maximum number of iterations.
Step 3 Randomly Choose a nest among n host nests say (j).
Step 4 Check if the solution F_i is less than the solution F_j then replace j by new solution.
Step 5 The nest with worst probability is treated as worst nest and is abandoned New ones are built. Keep the best nest or solutions
Step 6 The solutions are ranked and find the current best.
Step 7 Continue the iterations till the maximum number of iterations reached.
Step 8 Display the results.

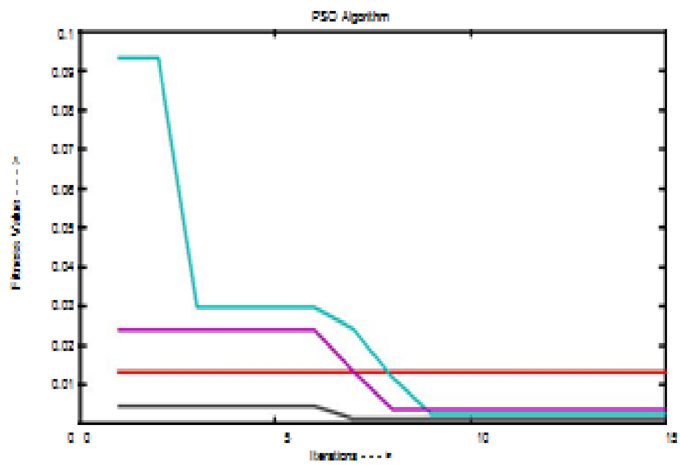
7. RESULTS AND ANALYSIS

MATLAB/SIMULINK is used to obtain the simulation model from the mathematical model of BLDC motor with Direct Torque control. The parameters used for the simulation of PMBLDC motor is given in Table 3.

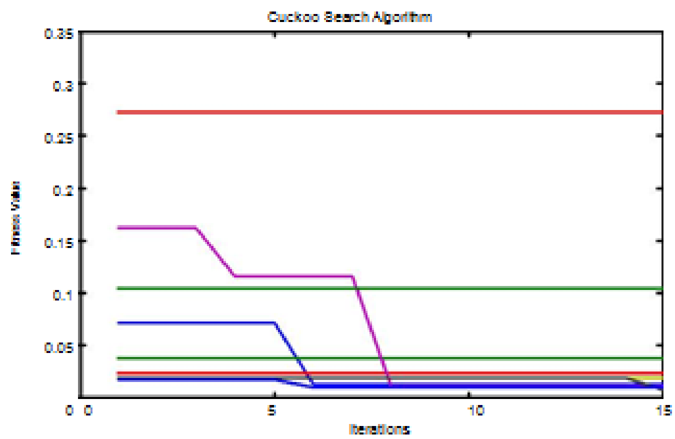
Table 3 PMBLDC motor parameters

Parameters	Values
Armature Resistance in Ohms	1.3
Armature Inductance in mH	0.85
Inertia(J) in Kgm^2	$8X10^{-3}$
Viscous damping (F) Nm-Sec	$1.349 X 10^{-5}$
No. of poles	4

The convergence of fitness function with different fitness values with respect to number of iterations for PSO tuned PI and CSA tuned PI are shown figures 2(a) and (b) respectively.



(a)



(b)

Figure 2 Objective function Vs Fitness value

(a) PSO Tuned PI Controller

(b) CSA Tuned PI Controller

The transient and steady state performance of the given BLDC motor with different controllers are analyzed. The current waveforms obtained by the use of PI, fuzzy, PSO-PI and CSA-PI controllers are shown in Figures (3), (4), (5) and (6) respectively. Smooth current waveform is achieved at starting when fuzzy, PSO-PI and CSA-PI controllers used. But a distorted waveform is obtained at starting when PI controller is used which will lead instability

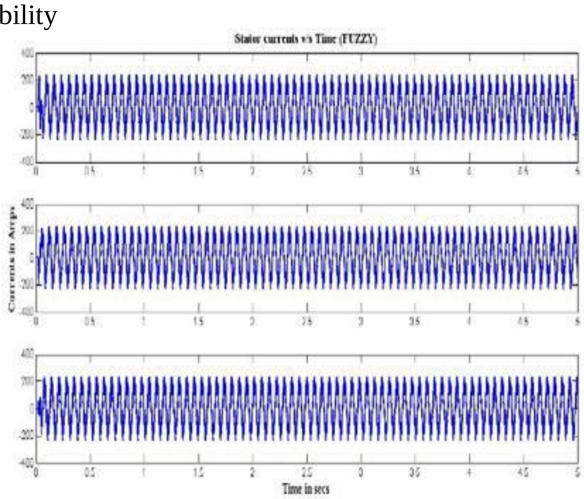


Figure 3 Stator Current Waveforms of PI Controller

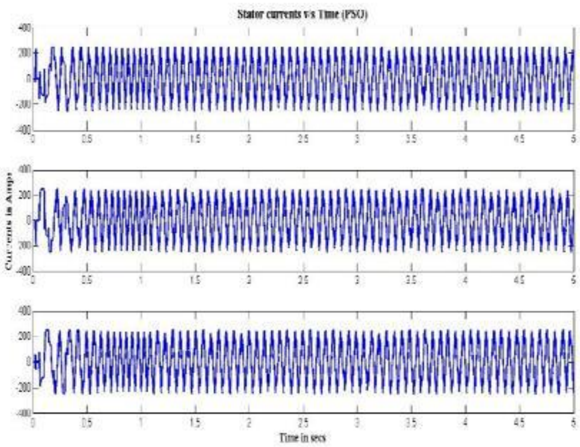


Figure 4 Stator Current Waveforms of Fuzzy Controller

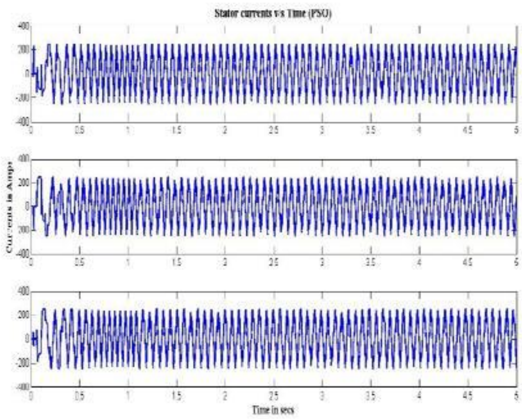


Figure 5 Stator Current Waveforms of PSO tuned PI Controller

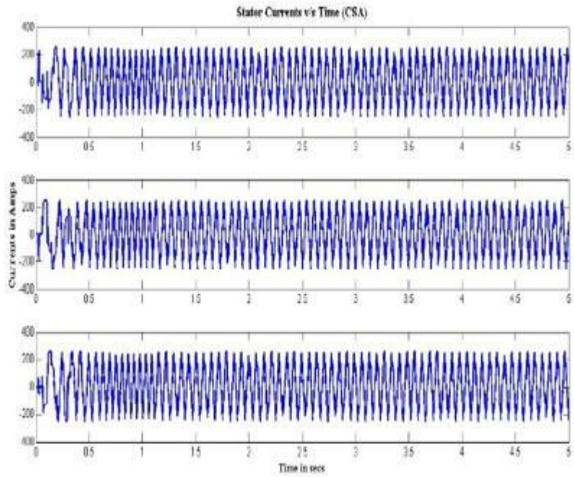


Figure 6 Stator Current Waveforms of CSA tuned PI Controller

The d- axis and q- axis fluxes are sinusoidal in nature and are phase shifted by 90 degrees each other. The flux curves for different controllers are shown in Figures (7), (8), (9) and (10). Form the figures, flux set up in the motor due to PI, PSO-PI and CSA-PI controllers are slightly distorted. But Fuzzy controller gives stable curve.

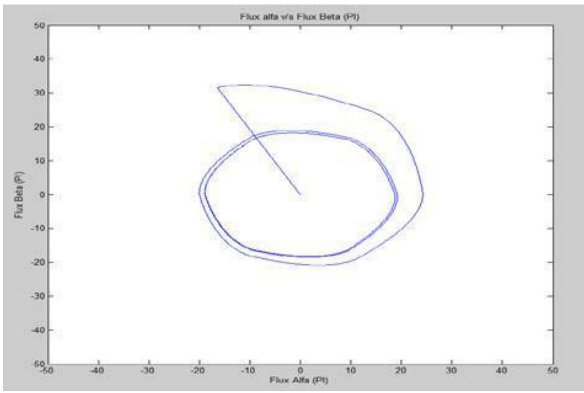


Figure 7 Flux distribution due to PI Controller

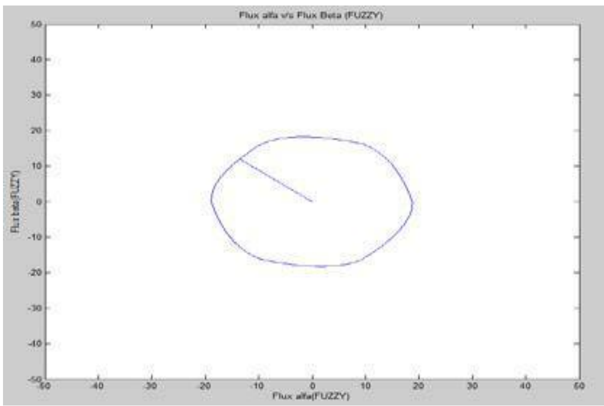


Figure 8 Flux distribution due to Fuzzy Controller

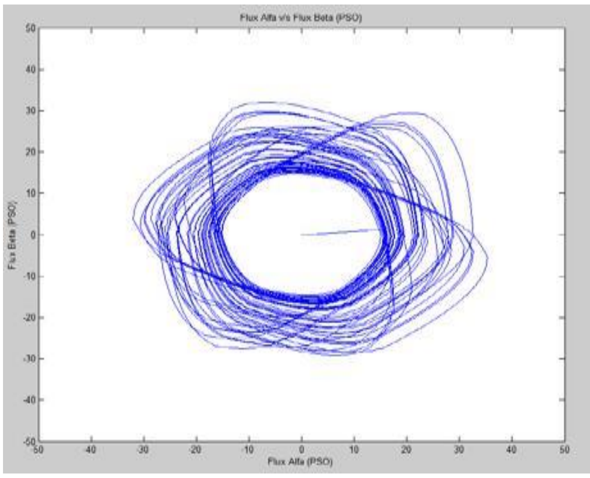


Figure 9 Flux distribution due to PSO-PI Controller

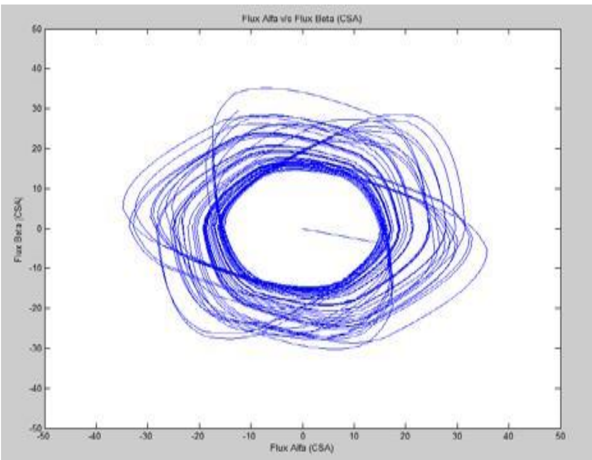


Figure 10 Flux distribution due to CSA-PI Controller

The speed response of the motor with different controllers is shown in Figure 11. From the speed curve, it is observed that PI and Fuzzy controller take 4 seconds to settle, whereas, PSO-PI and CSA-PI controllers take only 1.2 and 1.15 second to settle respectively. Therefore, it is concluded that PSO and CSA based control algorithm ensure the system stability earlier than PI and Fuzzy based control algorithm. By the performance of different controllers, it is proposed to implement CSA-PI control algorithm. Further the torque response is also tested with CSA-PI and PSO-PI control algorithm and is shown in Figure 12. Even some ripples at the time of starting for a very short duration, it settles immediately and ensure the stability in the operation.

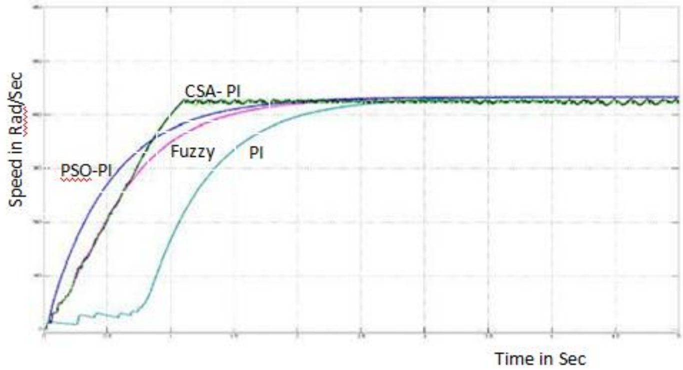


Figure 11 Speed responses of the motor with different control algorithms

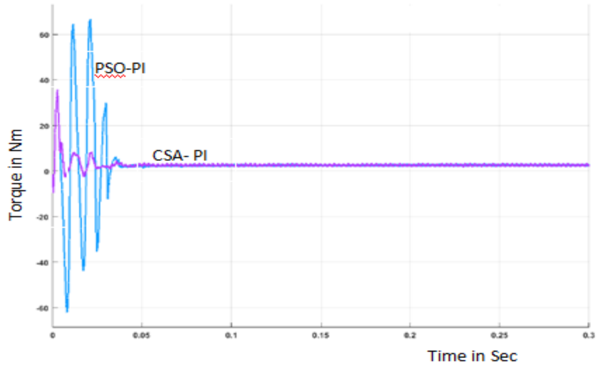


Figure 12 Torque responses of PSO-PI and CSA-PI algorithms

The efficiency of the motor with different control algorithm is also computed. Even though the entire all the algorithms produce the efficiency more than 90%, the CSA

S. NO.	**Parameters**	**Type of Controllers**				
		PI	**PID**	**FUZZY**	**PSO-PI**	**CSA-PI**
1	Efficiency in %	92.1	92.4	92.8	94.5	94.6
2	Rise time(s)	0.9	0.7	0.6	0.49	0.5
3	Peak time(s)	2.01	1.87	1.6	0.8	0.9
4	Settling time(s)	2.3	2.2	2.2	1.1	1.2
5	Steady state error	5.5	3.4	4.4	0.1	0.2

Table 4 Comparative Results with Different Controllers

8. CONCLUSION

The Direct Torque Control of PMBLDC motor is carried out using Matlab/Simulink and M-file. The results obtained from implementation of PI controller, PID controller, fuzzy logic based controller, PSO-PI and CSA-PI controllers are compared. The parameters for comparison were chosen are settling time, rise time and the peak overshoot in the speed waveform. The speed graph shows that the CSA and PSO gives better results compared to the PI, PID and fuzzy logic controller. The steady state error in the case of PSO-PI and CSA-PI controllers is very minimal compared with other controllers under consideration and therefore earlier stability is ensured in case of PSO-PI and CSA-PI controllers. A comparison on efficiency is also carried out. The efficiency under PSO-PI and CSA-PI controllers is significantly improved in comparison with other controllers. Overall, it is found that the Optimized PI using the PSO and the CSA algorithm performs better than the PI ,PID and the Fuzzy logic controlled DTC.

9. REFERENCES

1. Byoung-Kuk Lee 2003, '*On the Feasibility of Four-Switch Three-Phase BLDC Motor Drives for Low Cost Commercial Applications: Topology and Control'*, IEEE Transactions On Power Electronics, Vol. 18, No. 1. Pp. 162-172.
2. French, C & Acarnley, P 1996, *'Direct torque control of permanent magnet drives',* IEEE Trans. Ind. Appl., vol. 32, no. 5, pp. 1080–1088.
3. Hongjun Chen, Jing Li and Xin Zhou, *"PSO-based Self-Tuning PI Control for STATCOM",* IEEE 7th International Power Electronics and Motion Control Conference, 2012.
4. Izaskun Sarasola 2011, *'Direct torque control design and experimental evaluation for the brushless doubly fed machine',* Energy Conversion and Management, Pp. 1226-1234.
5. JianCheng Fang, Haito Li and BangCheng Han 2012, *"Torque Ripple Reduction in BLDC Torque Motor with Non Ideal Back EMF",* IEEE Transactions on Power Electronics, Vol.27, No.11.
6. Joong-Ho Song and Ick Choy 2004, *"Commutation Torque Ripple Reduction in Brushless DC Motor Drives using a Single DC Current Sensor",* IEEE transactions in Power Electronics, Vol.19, No.2
7. Kang, S.J. & Sul, S.K. 1995, *'Direct torque control of brushless DC motor with non ideal trapezoidal back-emf', IEEE Transactions on Power Electronics,* vol.10, no.6, pp.796-802.
8. Kumar, p, Nema, S & Padhy, P.K 2014, *'Design of Fuzzy Logic based PD Controller using Cuckoo Optimization for Inverted Pendulum',* Proceedings of International Conference on Advanced Communication Control and Computing.
9. Low, T. S, Tseng, K. J, Lee, T. H, Lim, K. W, & Lock, K. S 1990, *'Strategy for the instantaneous torque control of permanent-magnet brushless DC drives',* Proc. IEE—Elect. Power Appl., vol. 137, pp. 355–363.
10. Mourad Masmoudi, Bassem El Badsi & Ahmed Masmoudi 2014, *'DTC of B4-Inverter Fed BLDC Motor Drives with Reduced Torque Ripple During Sector-to-Sector Commutations'*, IEEE transactions on power electronics, vol.29, No.9, pp.4855-4865
11. Ramin Salehi Arashloo, Luis Romeral, Mehdi Salehifar & uan Manuel Moreno-Eguilaz 2014, *'Genetic algorithm-based output power optimization of fault tolerant five-phase brushless direct current drives applicable for electrical and hybrid electrical vehicles',* IET Electric Power Applications.
12. Sung, P.J, Han, W. P., Man, L. H. & Harashima, F 2000 *"A new approach for minimum-torque-ripple maximum-efficiency control of BLDC motor," IEEE Trans. Ind. Electron.*, vol. 47, no. 1, pp. 109–114.
13. Xin-she Yang & Suash Deb 2009, *'Cuckoo Search Via Levy Flights',* Proceedings of World Congress on Nature & Biologically Inspired Computer.
14. Yong Liu 2005, *"Direct Torque Control of Brushless DC Drives With Reduced Torque Ripple",* IEEE Transactions on Industry Applications, Vol. 41, No. 2, Pp. 599-608.
15. Zhang, X.Z & Wang, Y.N 2011, *'A novel position-sensorless control method for brushless DC motors',* Energy Conversion and Management, pp.1669-1676.
16. Geetha, V & Thangavel, S 2016, *'Optimized Proportional Integral Control for Direct Torque Control of PMBLDC Motor Using Meta Heuristic Methods'*, International Journal of Printing, Packaging & Allied Sciences, Vol. 4, No. 5, pp. 2944 – 2957.