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Performance Improvement for BLDC Motor by using Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

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***Abstract**: In this project ANFIS based control of BLDC motor is presented. Brushless DC motors (BLDC) find wide applications in industries due to their high power density and ease of control.To achieve desired level of performance the motor requires suitable speed controllers. The mathematical model of BLDC motor and a back propagation Adaptive Neuro-Fuzzy Inference Systems (ANFIS) algorithm are considered and included to replace the conventional method of Proportional Integral and Fuzzy. ANFIS it integrates both neural networks and fuzzy logic principles, it has potential to capture the benefits of both in a single framework. Its inference system corresponds to a set of fuzzy IF–THEN rules that have learning capability to approximate nonlinear functions. Hence, ANFIS is considered to be a universal estimator. The analysis of overshoot, rise time and steady state error for the speed range which indicates that the proposed adaptive neuro-fuzzy inference systems has successfully improved the performance of the BLDC motor drive. According to new proposed approach speed control of BLDC motor drive and analysis using adaptive Neuro-Fuzzy inference systems to carry off the weakness of fuzzy logic controller (Steady-state error).Further the ANFIS controller provides low torque ripples and high starting torque. The proposed ANFIS controller is evaluated by using MATLAB/SIMULINK software.*

Keywords- Brushless DC motor (BLDCM), Fuzzy Logic Speed Controller (FLC), Hysteresis Current Controller (HCC), PI Speed ControllerAdaptive Neuro-Fuzzy Inference Systems (ANFIS).

I. INTRODUCTION

The Permanent magnet brushless motors arecategorized into two types based upon the back EMFwaveform, brushless AC (BLAC) and brushless DC(BLDC) motors. BLDC motors are rapidly becomingpopular in industries such as Appliances, electrictraction, aircrafts, military equipment, hard disk drive, Industrial automation equipment, Instrumentation because of their high efficiency, high power factor, silent operation, compact, and reliability and low maintenance. BLDC motors have many advantages over DC motors and induction motors. [1-3]. Some of the advantages are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges. Fuzzy logic is widely used inmachine control. The term "fuzzy" refers to the fact that the logic involved can deal with concepts thatcannot be expressed as the "true" or "false" but ratheras "partially true". Fuzzy logic is an approach tocomputing based on "degrees of truth" rather than theusual "true or false" (1 or 0) Boolean logic on whichthe modern computer is based Fuzzy logic can beconsidered as a mathematical theory combining multi valued logic, probability theory. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PID or controllers and have better noise rejection capabilities. In this paper, fuzzy logic controller (FLC) is used for the control of the speed of the BLDC motor [4-7].

The torque of the BLDC motor is mainly influenced by back emf waveform. The ratio of torque delivered to the size of motor is higher, making it useful for applications where space and weight are critical factors. Generally the BLDC motors have trapezoidal back emf waveforms are fed with rectangular stator currents, which gives a constant torque. However in practice torque ripple exists mainly due to the emf waveform imperfections, current ripple and phase current commutation. This paper explains about the simple motor model of a BLDC motor and analyses the torque ripple reduction through PI speed [8-11] controller and fuzzy logic controller.

DC motor plays a significant role in modern industry. The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at thatspeed. There are numerous applications where control of speed is required [12], as in rolling mills, cranes, hoists, elevators, machine tools, transit system and locomotive drives. Usages stated above may request fast control exactness and great element reactions.

In BLDC motor the powerlosses are in the stator where heat can be easilytransferred through the frame or cooling systems areused in large machines. BLDC motors have manyadvantages over DC motors and induction motors [13].

Some of the advantages are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation; higher speed ranges. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or controllers and have better noise rejectioncapabilities.

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The aim of this paper is that it shows the dynamics response of speed with design the fuzzy logic controller to control a speed of motor for keeping the motor speed to be constant when the load varies. This paper is present design and implements a voltage source inverter for speed control of BLDC motor [14-15].

II. MATHEMATICAL MODELING OF BLDC MOTOR

Modeling of BLDCM often evolves in a manner resembling to a three phase synchronous machine. TheBLDCM is equipped by three phase voltage supply. The only requirement is that it should not be beyond the maximal voltage value of the BLDCM. Fig.1 depicts model of BLDCmotor drive. The voltage equation matrix for the BLDC motor are often represented as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where L denotes self-inductance and R denotes stator resistance, *va, vb, vc*denotes phase voltages, *ia, ib, ic*re motor currents and *ea, eb, ec*are trapezoidal back EMF (BEMF) of corresponding phases.

As it has been assumed that saturation and iron losses of the motor are unusually small, the stator resistances are identical and also the self-inductance of all phases is the same. The mutual inductance among the phases is identical to each other; and they are signified as

$$L_{aa} = L_{bb} = L_{cc} = L_s$$
$$L_{ab} = L_{ba} = L_{bc} = L_{cb} = L_{ac} = L_{ca} = M_m \quad (2)$$

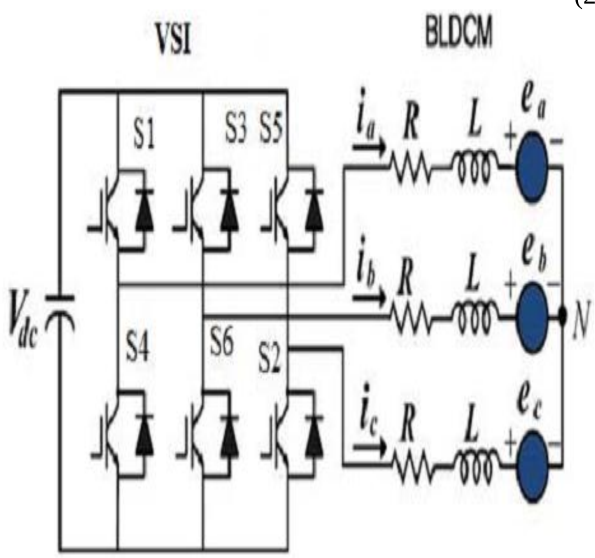


Fig.1. Model of BLDC motor drive

Hence, the equation (1) can be rewritten as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M_m & M_m \\ M_m & L_s & M_m \\ M_m & M_m & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3)$$

In a 3-phase BLDCM, the BEMF waveform depends on rotor position. BEMF of each phase has 120^{o}phase difference with others, thus the equation of every BEMF phase will be as represented as follows

$$e_a = K_b f_{as}(\theta)\ \omega \quad (4)$$

$$e_b = K_b f_{bs}(\theta)\ \omega \quad (5)$$

$$e_c = K_b f_{cs}(\theta)\ \omega \quad (6)$$

WhereKb is Back EMF constant [V/rad/Sec], θis rotor angle [in electrical degrees], ω is the speed of rotor [rad/Sec],and*fas, fbs, fcs* are trapezoidal functions.The trapezoidal function *fas*(θ) can be represented as

$$f_{as}(\theta) = \begin{cases} \dfrac{\theta}{\pi/6} & where \quad 0 < \theta \le \dfrac{\pi}{6} \\ 1 & where \quad \dfrac{\pi}{6} < \theta \le \dfrac{5\pi}{6} \\ 1 - \dfrac{(\theta - \frac{5\pi}{6})}{\pi/6} & where \quad \dfrac{5\pi}{6} < \theta \le \dfrac{7\pi}{6} \\ -1 & where \quad \dfrac{7\pi}{6} < \theta \le \dfrac{11\pi}{6} \\ -1 + \dfrac{\left(\theta - \frac{11\pi}{6}\right)}{(\pi/6)} & where \quad \dfrac{11\pi}{6} < \theta \le 2\pi \end{cases} \quad (7)$$

The functions *fbs (θ)* and*fcs (θ)* can be expressed as

$$f_{bs}(\theta) = f_{as}\left(\theta + \frac{2\pi}{3}\right) \quad (8)$$

And

$$f_{cs}(\theta) = f_{as}\left(\theta - \frac{2\pi}{3}\right) \quad (9)$$

The functions *fas (θ)*,*fbs (θ)*, *fcs (θ)* have the identical shape as e_{as},e_{bs} and e_{cs} with a maximum magnitude of±1.

The rotor angle (θ) in electrical degrees is related to therotor angle in mechanical degrees (θm) and number of pole pairs (P) as follows

$$\theta = \frac{P}{2}\theta_m \quad (10)$$

The electromagnetic torque Te can be stated as the followingequation

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (11)$$

The equation of a motor with inertia J, friction coefficient Band load torque T_l is expressed as

$$T_e - T_l = J\frac{d\omega}{dt} + B\omega \quad (12)$$

III. DESIGN OF SPEED CONTROLLER

The controller design applied to aBLDC motor with a trapezoidal BEMF for yielding anacceptable speed control performance. The fundamental diagram of BLDCM for controlling speed is depicted in Fig.2.

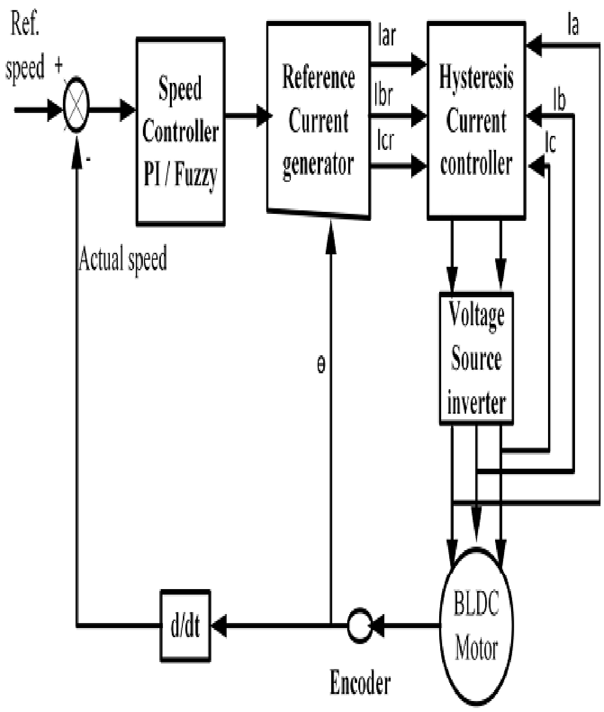


Fig.2. Fundamental diagram for BLDCM speed regulation

The BLDC motor works on speed and current control mode. In the prior mode, the motor speed is differentiated with reference speed, based on this the amount of current in each phase is altered. In the later mode, the actual current in each phase has been compared with reference current and an error here is being processed through HCC. The HCC brings out required pulses for the suitable switching of inverter.

a) PI speed controller

This kind of controller is used in the majority of industrial applications due to its lucid control structure. Here, the PIcontroller's output is expressed by the subsequent equation

$$V_c(t) = K_{pr}\ E_r(t) + K_{in}\int_0^t E_r(t)\ dt \quad (13)$$

Where(t) the PI speed controller's output, Kpr is proportional gain, Kin is integral gain and Er(t) is error signal. The definite speed of the BLDC motor correlates with the required speed. The typical PI controller is depicted in Fig.3.

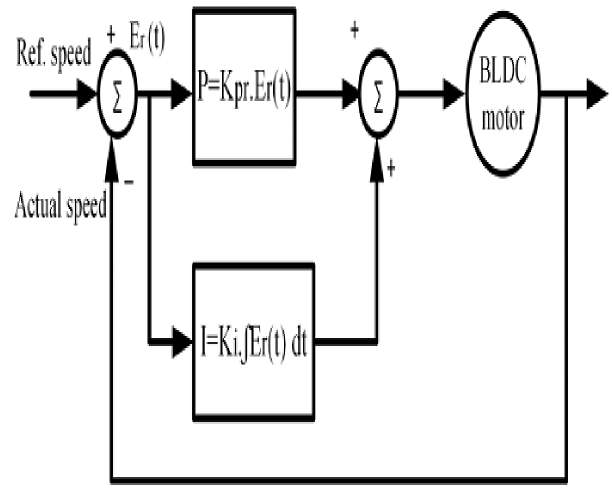


Fig.3. PI controller

b) Fuzzy Logic Controller

Fig.4 depicts basic block diagram of a FLC. FLC does not need precise mathematical model for a system. It has been designed based on the experience of people. The primary step inside the FLC is fuzzification. It is a method that converts crisp inputs to linguistic variables. These linguistic variables are quantified by using membership functions. The most common kinds of membership functions are triangular and trapezoidal shapes. In general, these are selected with the user expertise.

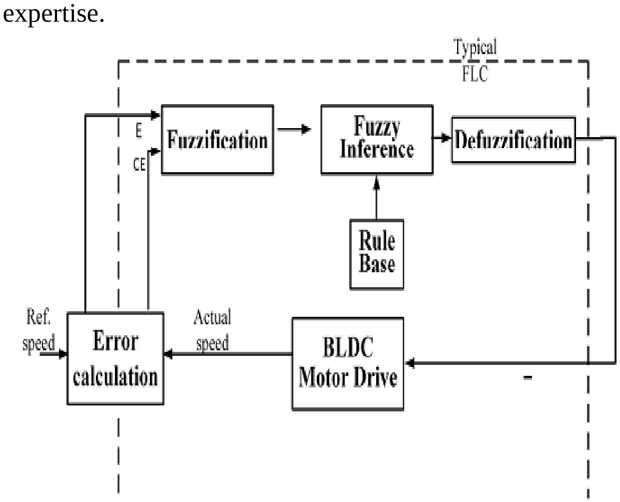


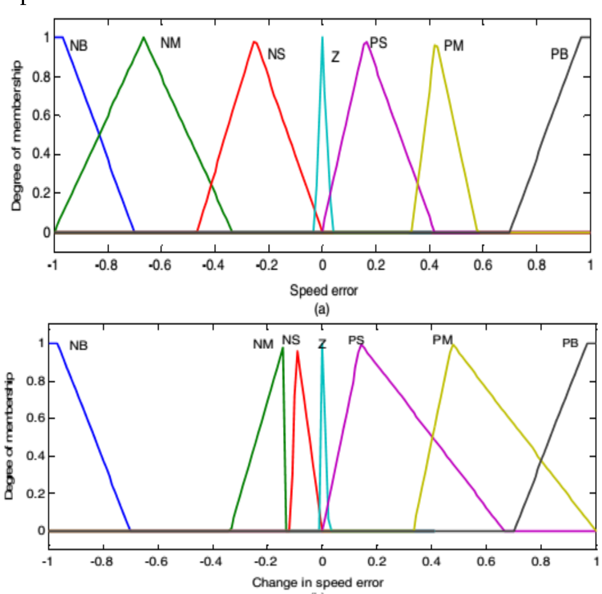
Fig.4. Basic structure of FLC

Later, by using rule base an inference is designed. Rule base has been built to manage output variable. It could be an elementary if-then rule consisting of an assumption and conclusion. After, determining the consequences of every rule, these are to be joined to get the final result. This method is named as inference [7]. A rule base applied for intended FLCis portrayed in Table 1. Fuzzy membership functions (MFs) are specified as Negative Big (NB), Negative Medium (NM),Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

Table.1. Rules of FLC

Error	Change in error						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

In case of controlling BLDCM, speed error (E) and changing speed error (CE) have been chosen as inputs to FLC. The output of the FLC is function of E and CE. For getting the most effective control execution, five triangular and two trapezoidal membership functions have been chosen. The opposite term of fuzzification can be defuzzification. Rules forFLC generate needed output in a linguistic variable. It is modified to crisp output. Making utilizing of 'centroid'defuzzification scheme, crisp output has been attained. Fig.3.5illustrates the MFs of input and output variable for effective control of a BLDCM.



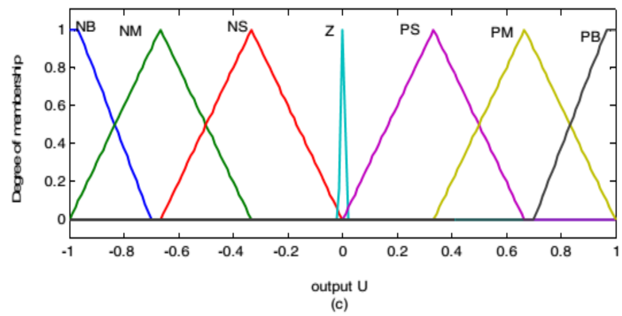


Fig.5. Membership functions of FLC

c) ANFIS

An adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference system. The technique was developed in the early 1990s. Since it integrates both neural networks and fuzzy logic principles, it has potential to capture the benefits of both in a single framework. Its inference system corresponds to a set of fuzzy IF–THEN rules that have learning capability to approximate nonlinear functions. Hence, ANFIS is considered to be a universal estimator. For using the ANFIS in a more efficient and optimal way, one can use the best parameters obtained by genetic algorithm.

For simplicity, it is assumed that the fuzzy inference system under consideration has two inputs and oneoutput. The rule base contains the fuzzy if-then rules of Takagi and Sugeno's type as follows:If x is A and y is B then z is f(x, y)where A and B is the fuzzy sets in the antecedents and z = f(x, y) is a crisp function in theconsequent. Usually f(x, y) is a polynomial for the input variables x and y. But it can also be any otherfunction that can approximately describe the output of the system within the fuzzy region as specifiedby the antecedent. When f(x, y) is a constant, a zero order Sugeno fuzzy model is formed which may beconsidered to be a special case of Mamdani fuzzy inference system [144] where each rule consequentis specified by a fuzzy singleton. If f(x, y) is taken to be a first order polynomial a first order Sugenofuzzy model is formed. For a first order two rule Sugeno fuzzy inference system, the two rules may bestated as:

Rule 1: If x is A1 and y is B1 then f1 = p1x + q1y + r1

Rule 2: If x is A2 and y is B2 then f2 = p2x + q2y + r2

Here type-3 fuzzy inference system proposed by Takagi and Sugeno is used. In this inferencesystem the output of each rule is a linear combination of the input variables added by a constant term.The final output is the weighted average of each rule's output. The corresponding

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equivalent ANFIS structure is shown in Fig.6.

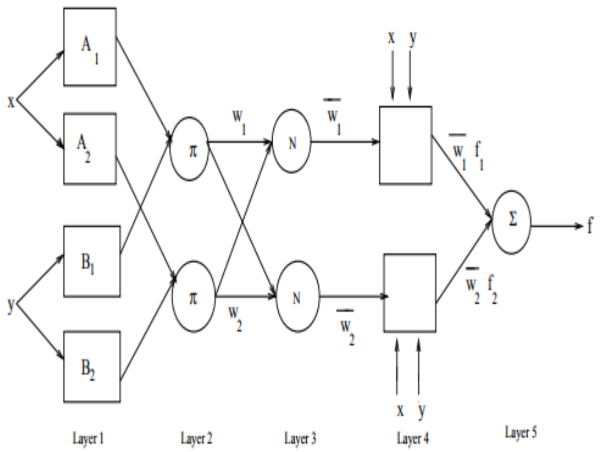


Fig.6 ANFIS Structure

IV. MATLAB/SIMULINK RESULTS

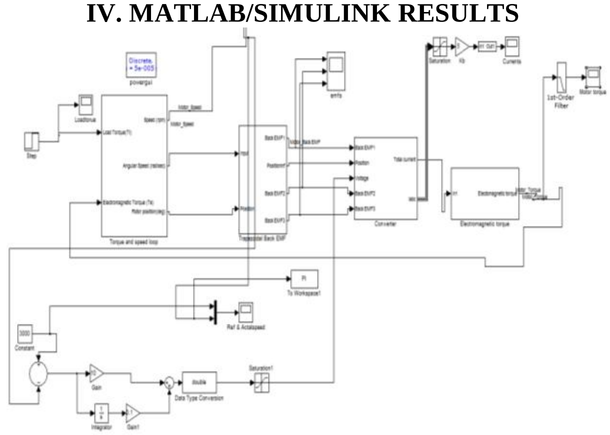
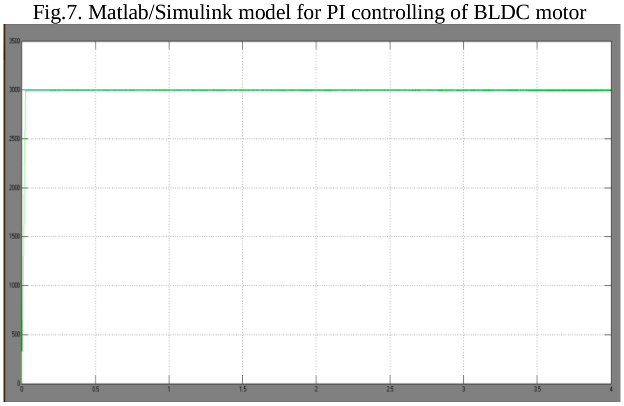
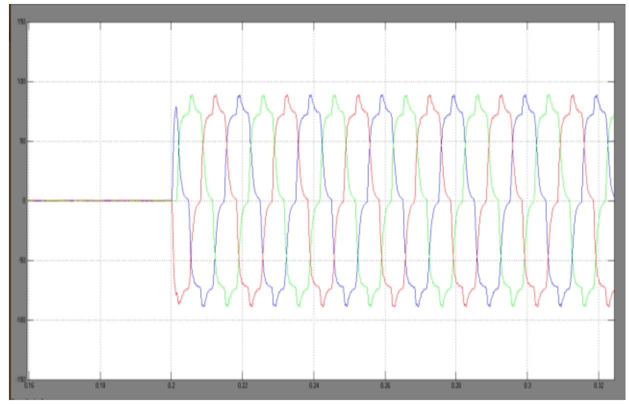


Fig.7. Matlab/Simulink model for PI controlling of BLDC motor



(a)



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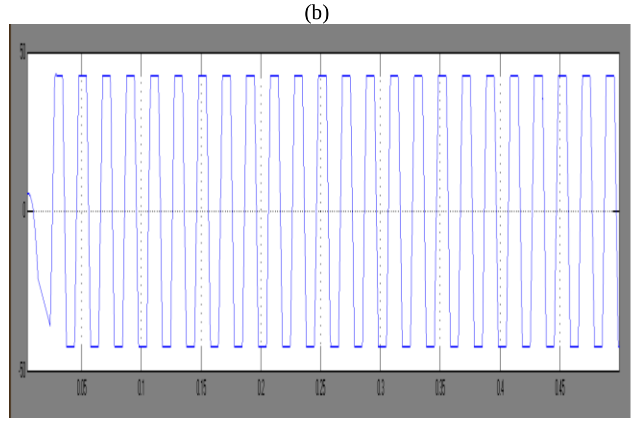

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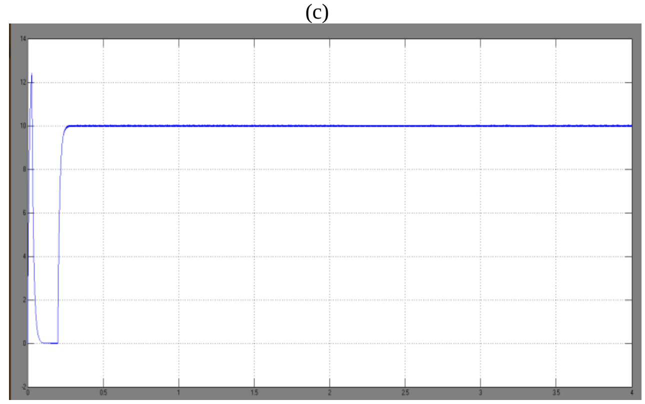


(d)

Fig.8. Performance of BLDC motor with PI controller at a Tl of 10 Nm applied at 0.2 Sec. (a) Speed (b) Phase A current Ia (c) Back Emf, Eba (d) Torque Te

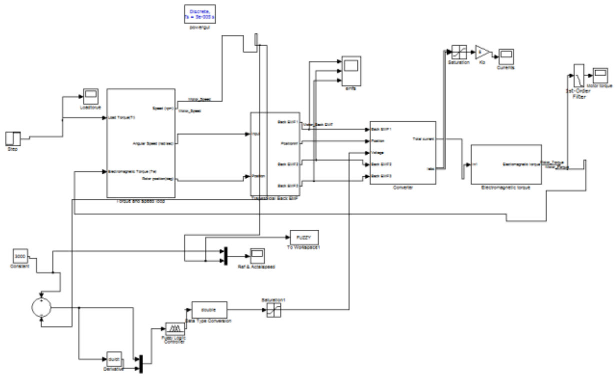
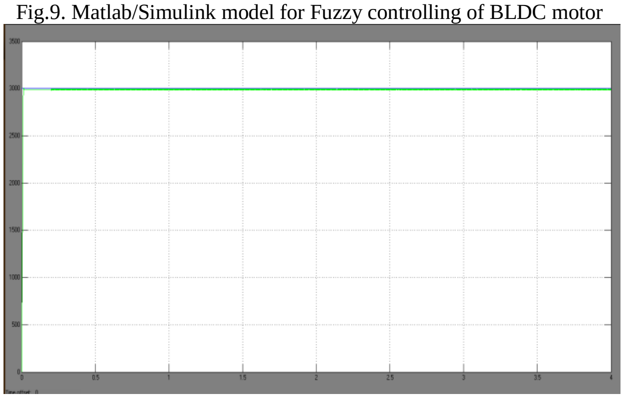
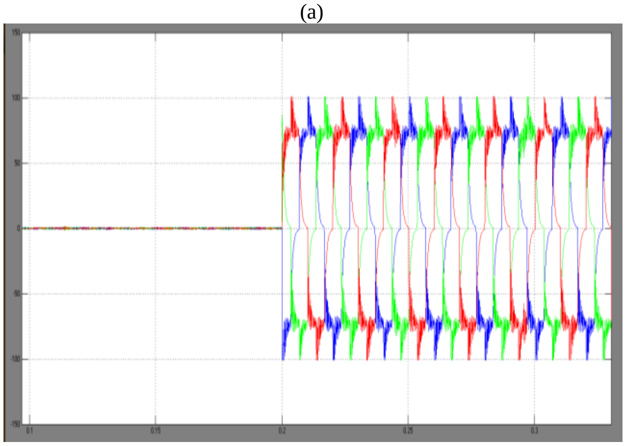


Fig.9. Matlab/Simulink model for Fuzzy controlling of BLDC motor



(a)



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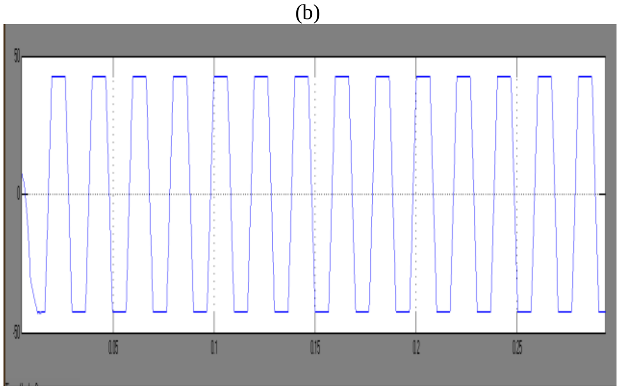

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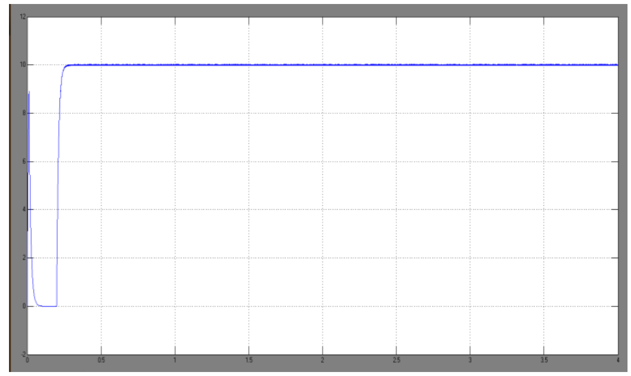

(d)

Fig.10. Performance of BLDC motor with Fuzzy controller at a load torque of 10 Nm applied at 0.2 Sec. (a) Speed (b) Phase A current Ia (c) Back EMF, Eba (d) Torque Te

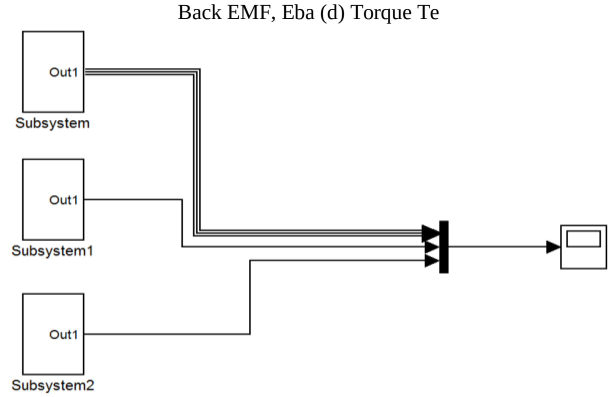

Fig.11. MATLAB/SIMULINK circuit of speed response of PI, FLC system

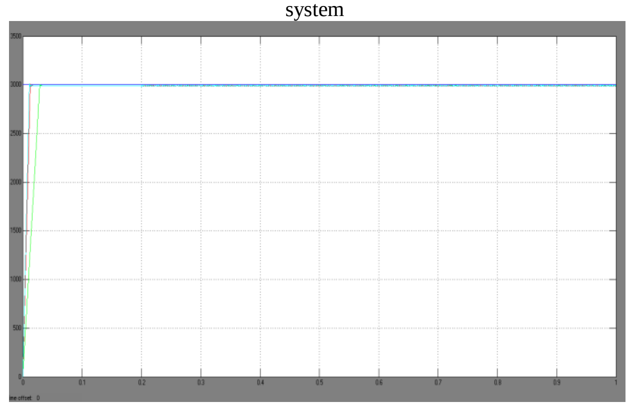

Fig.12. Comparison of speed response of PI, FLC at 3000 rpm for T_l of 10 Nm

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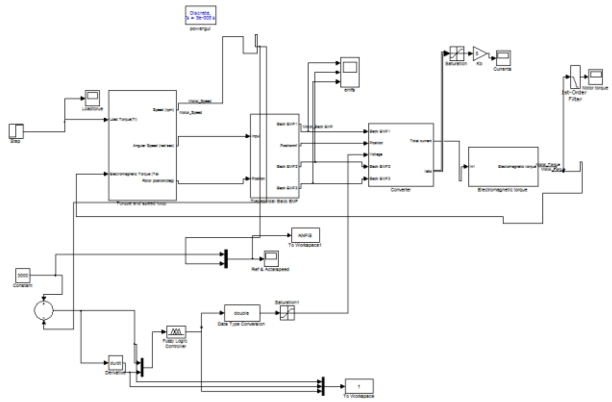
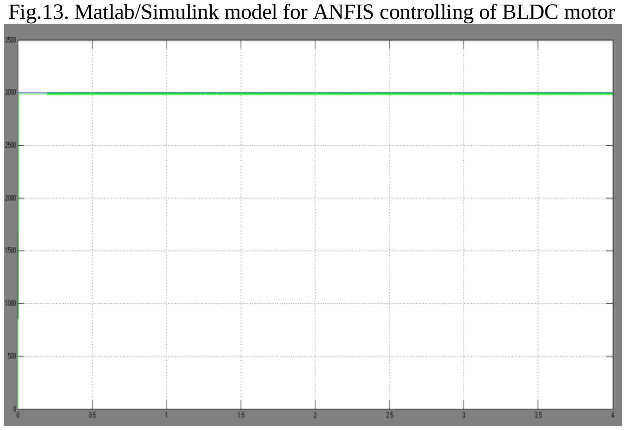
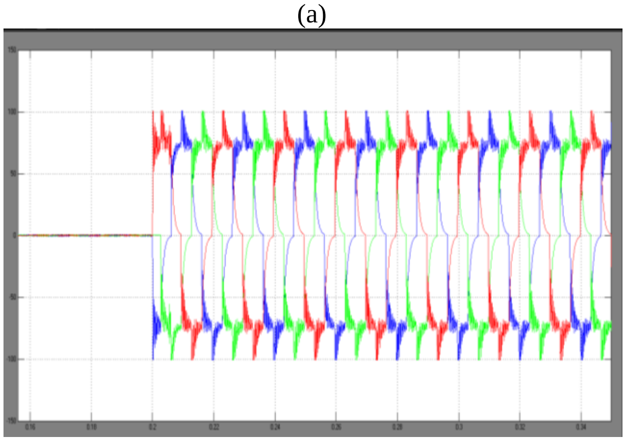


Fig.13. Matlab/Simulink model for ANFIS controlling of BLDC motor



(a)



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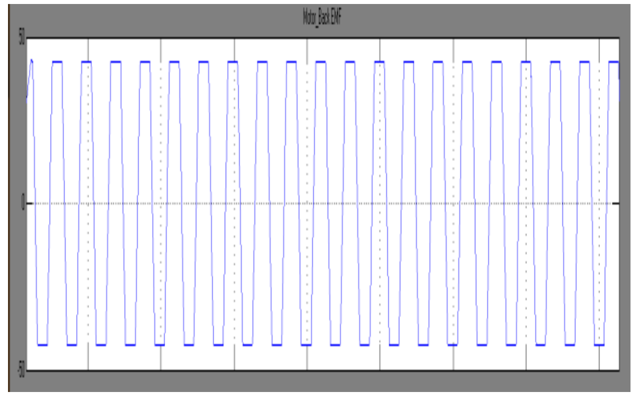

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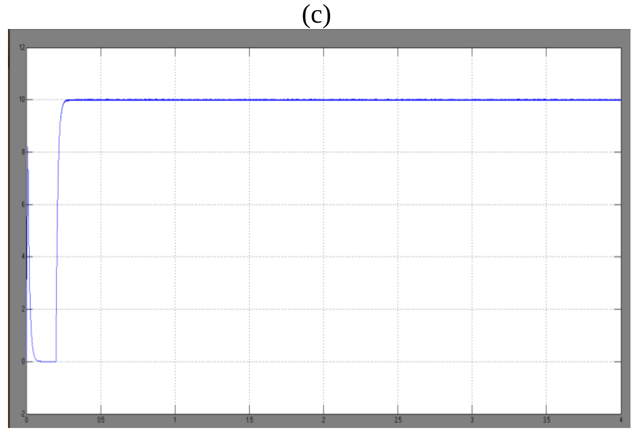

(d)

Fig.14. Performance of BLDC motor with ANFIS controller at a load torque of 10 Nm applied at 0.2 Sec. (a) Speed (b) Phase A current Ia (c) Back EMF, Eba (d) Torque Te

V. CONCLUSION

In this paper, the mathematical modeling of BLDC motor and the speed control of the BLDC motor byusing fuzzy logic and PID controller and ANFIS has been proposed and verified. Fuzzy logic controller (FLC) and Neuro-FuzzyContoller have been employed for the speedcontrol of DC motor drive and analysis of theperformance for both of the controller schemesis studied. This research work proposes a modelfor speed control of brushless DC motor driveusing Fuzzy Logic Controller (FLC) and Neuro Fuzzy Contoller. The speed of a separately excited BLDC Motor can be successfully controlled by using Neuro-Fuzzy Contoller technique. It was analyzed that the Neuro-Fuzzy controller gives better results rather than the Fuzzy logic controller.The principle of operation, design considerations and simulation results has been presented. The proposed strategy is suitable for both small ratings and large ratings of BLDC drives with low cost. It is an effective strategy to improve the speed in BLDC drives.

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