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Adaptive Neuro Fuzzy Technique for Speed Control of Six-Step Brushless DC Motor

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Abstract—The brushless DC motors with permanent magnets (PM-BLDC) are widely used in a miscellaneous of industrial applications. In this paper, The adaptive neuro fuzzy inference system (ANFIS) controller for Six-Step Brushless DC Motor Drive is introduced. The brushless DC motor's dynamic characteristics such as torque , current , speed, , and inverter component voltages are showed and analysed using MATLAB simulation. The propotional-integral (PI) and fuzzy system controllers are developed., based on designer's test and error process and experts. The experimential and hardware resuts for the inverter- driver circuits are presented. The simulation results using MATLAB simulink are conducted to validate the proposed (ANFIS) controller's robustness and high performance relative to other controllers.

Index Terms- Adaptive neuro-fuzzy inference system, Six Step Control, fuzzy logic Control, Brushless DC Motor.

I. INTRODUCTION

Brushless DC motors are now commonly used in numerous uses, from motor vehicles to automotive applications for power systems to aircraft. The key reason for increased use of brushless DC motors can be traced to a strong weight / size ratio, Great acceleration efficiency, low to no maintenance and less acoustic and electrical noise than the Brushed DC motors[1]. It has contributed to major work on the BLDC motors for speed modulation.

A brushless DC motor is a synchronous electrically powered motor which is powered by DC electrical current and it is different than dc motor because of its electronically commutation control, instead of the old way of a mechanical commutation system which uses brushes.

PID still very preferred in industry and at many automatic control applications, and it also used with BLDC motor, but the problem which rises with PID technique are the non-linear systems, the problem of affecting the speed after adding any additional loads, suffering from changing dynamics after a long time operation which will be very difficult to be covered with a fixed PID controller [2]. Moreover, the external noise which make PID controller not be the perfect choice to control the BLDC motor in these circumstances because it means that we need to change the parameters dynamically. The method of

Proportional Integral and Derivative (PID) control is primarily used in the industry. Easy structure and stable service necessarily gain . Even in today's scenario, more than 95% of closed loop industrial controllers are PI or PID based [5]. R. Kandiban, R. Arulmozhiyal suggested an improved adaptive Fuzzy PID controller for brushless DC motor speed control in [4]. The simulation and experimental results show that the Fuzzy logic controller [6], effectively and efficiently control the brushless direct current motor (BLDC). The comparsion between fuzzy controller and PI controller is given for speed control of BLDC motor using MATLAB simulation [7].

Various modern artificial intelligence based methods were proposed to cater for the nonlinear variation of BLDC motor parameters. A neuro Fuzzy interface that makes our environment responsive by the use of teaching , learning and measuring strategies that enhance performance [3].

The contributions of the paper are represented in the following points,

- This paper demonstrates an improved (ANFIS) speed controller for BLDC motor drive.
- The PI and fuzzy controllers are utilized as a conventional technique depend on the trial and error method and designer's expertise methods.
- The suggested (ANFIS) controller compared with The PI and fuzzy controllers are carried out. The contrast highlights the suggested superiority (ANFIS).
- The practical and experimental results for inverter and motor drive are presented.

The rest of this paper is sorted out as follows: Section II gives a short portrayal and numerical plan of Six-Step BLDC motor drive operating principle and model equations . In Section III, the idea of fuzzy control system is discussed. In section IV, the concept of **(ANFIS)** is illustrated in section V. Section VI demonstrates the simulaion model with controllers. The results and discussion are in section VII. In final, the conclusions of the research are in Section VIII.

II. BLDC MOTOR OPERATING PRINCIPLE AND MODEL

a. Operating Principle

A brush less dc motor is known as a synchronous permanent machine with feedback from rotor position. A three-phase voltage semiconductor bridge is commonly used to monitor the brushless motors. The motor needs a rotor location sensor to turn on the control devices in the inverter bridge to provide a correct switching sequence. The control devices are commuted sequentially every 60 degrees, depending on the rotor location. Of this purpose, electronic commutation is used instead of swapping the armature current using brushes. It removes the issues related to the brush and the switching system, such as sparking and rubbing out of the switching brush system, thereby making a BLDC more durable than a dc motor [9], [10] .

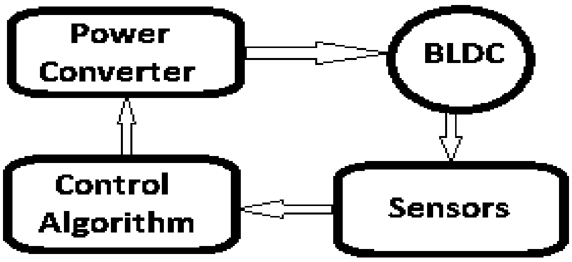

Fig1. Basic block diagram of BLDC motor

The brushless dc motor foundation block diagram, as seen in figure 1. Four key components power converter, permanent magnet-synchronous system (PMSM) sensors and control software make up the brush less dc motor. The power converter converts power from the source to the PMSM which converts electrical energy into mechanical energy. One of the key features of the less dc brush motor is the rotor position sensors, based on the position of the rotor and the command signals, which may be the torque control, the voltage control, the speed control, and so on. Control algorithms are used to evaluate the gate signal for every semiconductor in the power electronic converter. The configuration of the control algorithms specifies the type of brush with less dc power, of which there are two major types of source-based drives and existing source-based drives. Either the source voltage and the source current drive are used in a permanent magnet synchronous system with either sinusoidal or non-sinusoidal back waveforms. The sinusoidal back emf mechanism (Figure.2) can be managed to produce almost constant torque. Nevertheless, the non-sinusoidal back emf system (Figure.3) bid increases inverter size and eliminates losses at the same power point [11],[12].

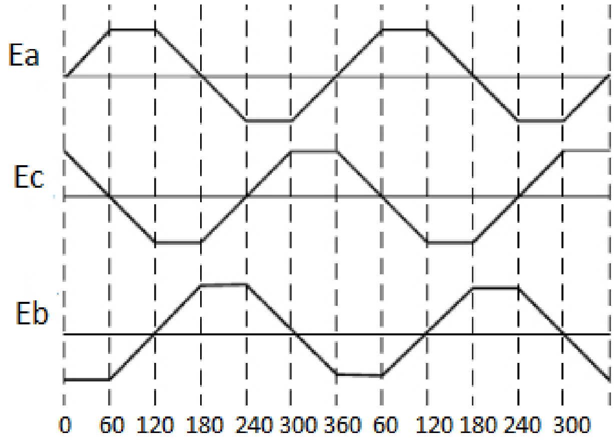

Fig2. Trapezoidal back emf of three phase BLDC motor

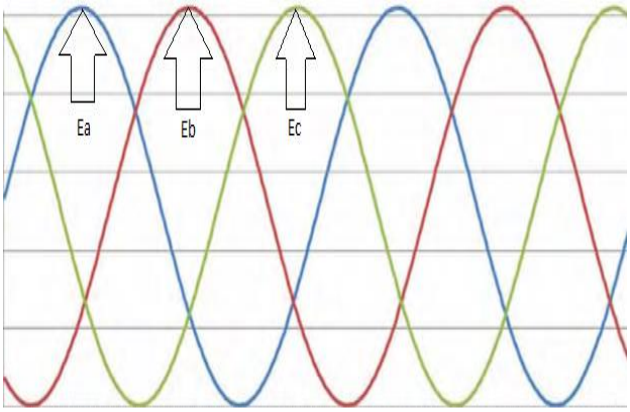

Fig3. Sinusoidal phase back emf of BLDC motor

b. BLDC MOTOR MODEL

A brushless DC motor is fitted with a rotor magnet and three stator windings. Thanks to the high resistance of both magnets and stainless steel, rotor-driven currents can be ignored. The voltage equations of the motor can be given as [8]:

$$V_a = i_a R_a + L_a \frac{dia}{dt} + M_{ab}\frac{dib}{dt} + M_{ac}\frac{dic}{dt} + e_a \quad (1)$$

$$V_b = i_b R_b + L_b \frac{dib}{dt} + M_{ba}\frac{dia}{dt} + M_{bc}\frac{dic}{dt} + e_b \quad (2)$$

$$V_c = i_c R_c + L_c \frac{dic}{dt} + M_{ca}\frac{dia}{dt} + M_{cb}\frac{dib}{dt} + e_c \quad (3)$$

Where e_a, e_b and e_c are the back emfs which are functions of rotor angle given by

$$e = K_b \omega_m \quad (4)$$

where K_b is the back emf constant. From the above equations, the following matrix can be deduced:

$$\begin{bmatrix} V_a \\ V_b \\ V_C \end{bmatrix} = \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

Since there is no saliency, self-inductance is independent of the rotor position. Therefore,

$$L_a = L_b = L_c = L \quad (6)$$

And mutual inductances

$$M_{ab} = M_{ba} = M_{bc} = M_{cb} = M_{ac} = M_{ca} = M \quad (7)$$

For a balanced three phase system, phase resistances are equal, i.e.,

$$R_a = R_b = R_c \quad (8)$$

Rearranging equations (5) , we get

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (9)$$

Electromagnetic torque can be expressed as:

$$T_{em} = j.\frac{d\omega r}{dt} + D\omega r + T_l \quad (10)$$

Electromagnetic torque depends upon back emf and rotor current and can be expressed as:

$$T_{em} = \frac{1}{\omega_m [e_a i_a + e_b i_b + e_c i_c]} \quad (11)$$

From the above equations, the transfer function can be deduced to be as follows:

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{K_t}{[(L_s + R)(Js + D) + K_t K_b]} \quad (12)$$

In the BLDC motor is fed a PWM inverter. Decoding the signals from the Hall effect produces signals from the inverter gates. It is based on the use of 6 different steps according to an angle of 60o electrical rotation. The term trapezoidal refers to the current waveform and the form of the back electromotive force that is produced by this process. Nevertheless, the 6-step algorithm is based on sensing the rotor's position using three hall sensors that are mounted in the drive motor. These hall sensors are installed every 120o, six separate commutations are possible with these sensors, and phase switching depends on the values of the hall sensors. Chart. figure.4, Presents schematics of the 6-Step method.

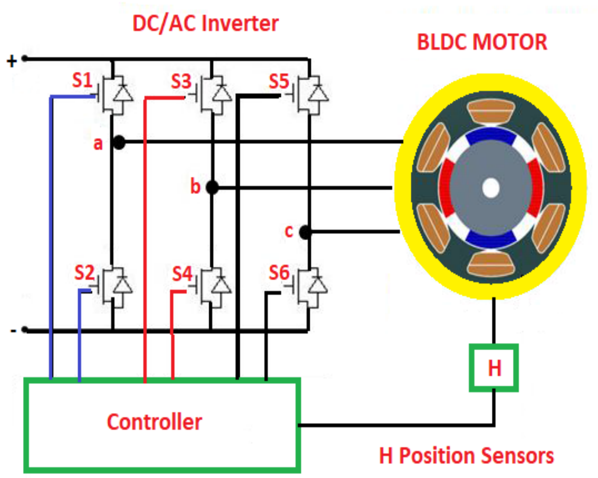

Fig. 4. Schematic of Six-Step Commutation model

III. PID CONTROLLER

At any process, we need to use a control technique to design convenient controller to overcome any error, minimize the error and to reach the desired target at minimum time. In the case of speed control we can define error of speed equation as:

$$e(t) = \omega d(t) - \omega a(t) \quad (13)$$

$$u(t) = k_P\ e(t) + k_I \int_0^t e(t)d(t) + k_D \frac{de(t)}{dt} \quad (14)$$

Where:

u(t) is the control signal from the controller.

k_P is the proportional gain of the controller.

k_I is the integral gain of the controller

k_D is the derivative gain of the controller.

$e(t)$ is the error function.

The following block diagram, in figure 5 explains the operation of PID controller.

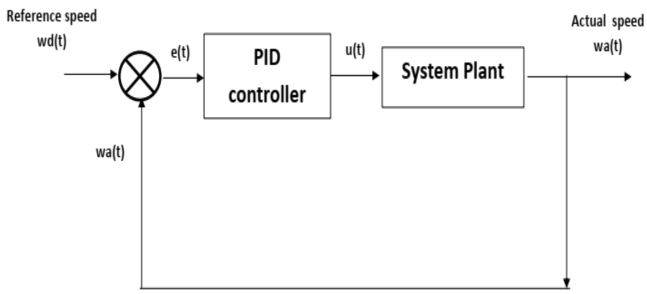

Fig. 5 : Block Diagram of a System with PID Controller.

IV. Fuzzy Logic Controller

The basic components of the Fuzzy Logic controller are: a knowledge base , fuzzification , inference engine, and an interface for defuzzisation. In fuzzy logic the addition of fuzziness to data is called fuzzification. Fuzzy linguistic definitions are formal device representations made by fuzzy rules of the IF-THEN. The following block diagram, in figure 5 explains the operation of our Fuzzy controller.

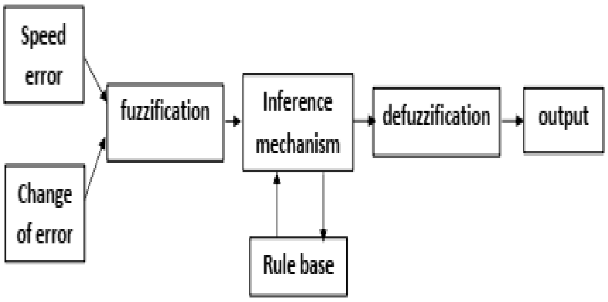

Fig. 5. Block diagram of Fuzzy Controller

V. Neuro-Fuzzy Controller

The ANFIS technique (Adaptive Neuro Fuzzy Inference system) simply constructs an input output network depends on feed forward learning techniques; its construction consists of nodes and links connecting these nodes which all of them are adaptive targeting to minimize error as possible by learning [13].

ANFIS lets linguistic and numerical data be combined. The neuro-fuzzy systems can acquire numerical knowledge of fuzzy, by comparsion. Within the adaptive neuro-fuzzy model , two simple learning algorithms are required. Another is the structural learning algorithm for discovering suitable fuzzy logic rules, and the other is the learning parameter algorithm for modifying membership functions and other parameters according to the performance of the target program [13]. Training algorithms of gradient-descent from the neural network field are used in this analysis. The approach is usually expressed as modelling Neuro-Fuzzy. Under the Takagi-Sugeno (TS) model, two fuzzy if-then rules are given as follows for communication of the ANFIS structure:

Rule 1: If (x is A1) and (y is B1) then f1 = p_1x+q_1y+r1

Rule 2: If (x is A2) and (y is B2) then f2 = p_2x+q_2y+r2

Here, r_i, p_i and q_i are the design parameters determined during the period of training phase.

ANFIS controller system's general block diagram designed for a fuzzy controller is shown in figure 6. the ANFIS controller method uses multi-iteration testing technique and hybrid learning algorithm.

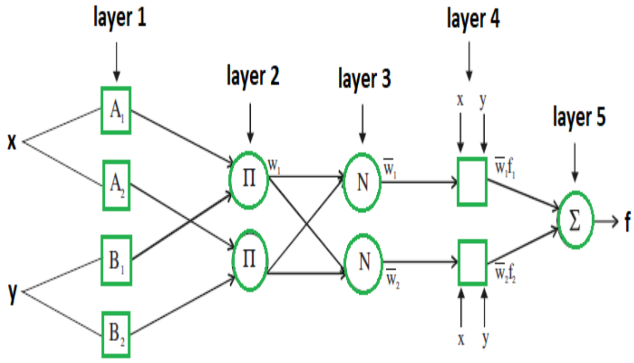

Fig. 6. A schematic diagram of ANFIS controller system.

all adjustable parameters are changed by ANFIS' learning or training algorithm to compare ANFIS output to trained data. The output of Fuzzy system z in eq (15).

$$z = \frac{w_1}{w_2+w_1} z_1 + \frac{w_2}{w_1+w_2} z_2$$
$$= \overline{w_1}(p_1x + q_1y + r_1) + \overline{w_2}(p_2x + q_1y + r_2)$$
$$= (\overline{w_1}x)p_1 + (\overline{w_1}y)q_1 + (\overline{w_1})r_1 + (\overline{w_2}x)p_2 + (\overline{w_2}y)q_2 + (\overline{w_2})r_2 \quad (15)$$

Nevertheless, if membership function parameters are not set and require adjustment the area to be trained becomes wider and convergence of training algorithm slows down. In such cases, the hybrid learning algorithm with combination of gradient descent and least- squares gives more effective results. The neuro fuzzy block diagram of BLDC motor shows in figure 7 .

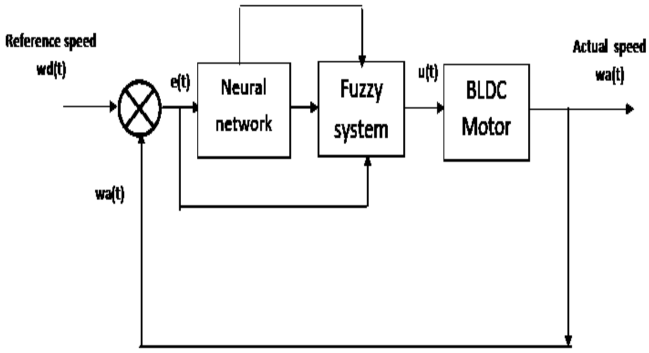

Fig. 7. Block diagram of Neuro Fuzzy Controller

SIMULATION MODELWITH CONTROLLERS

The Six-Step BLDC Motor has been simulated with controller in the MATLAB/SIMULINK environment as shown in figure 8. The various parameters used for simulation are listed Table 1 in the Appendix.

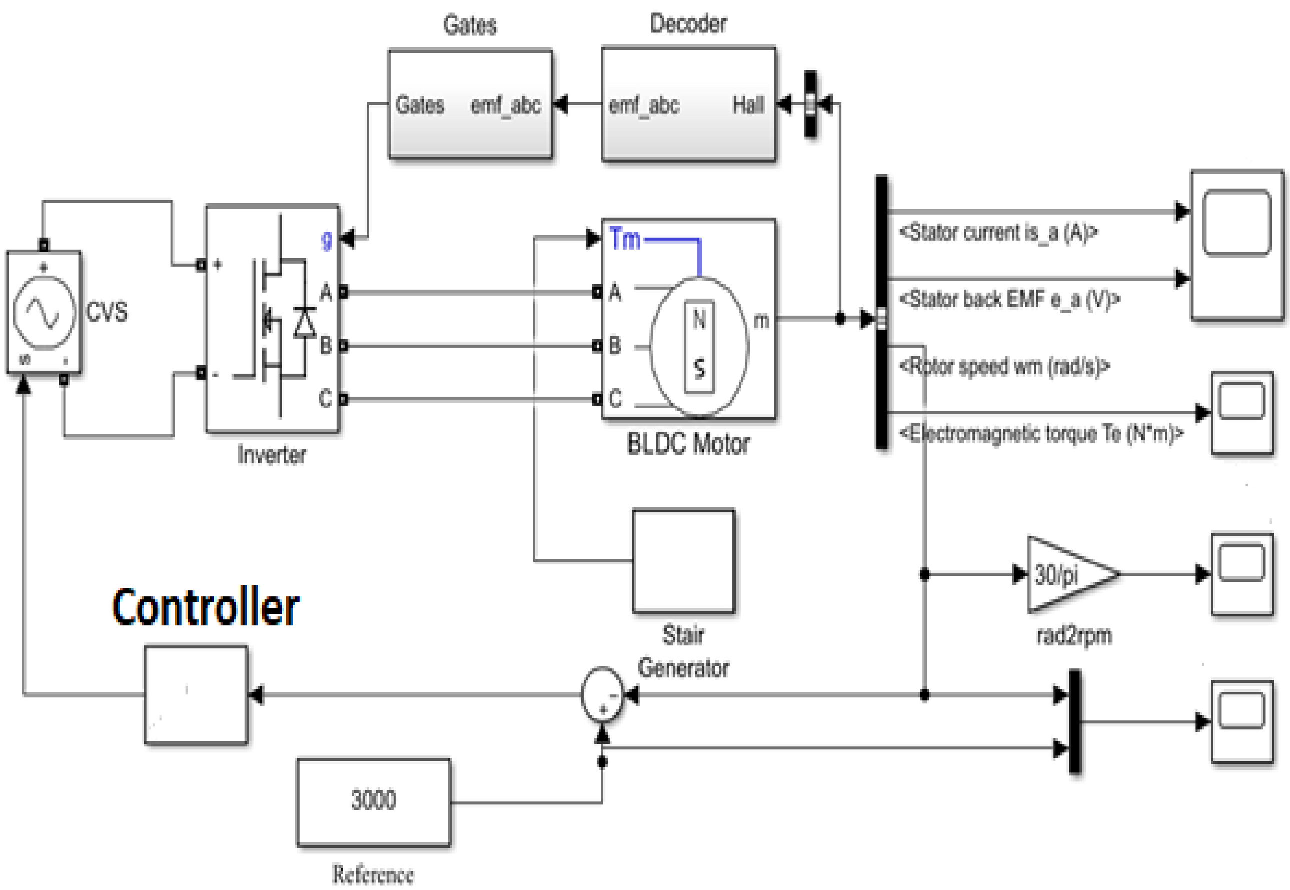

Fig. 8. Simulation model of BLDC motor with controller.

- **PID CONTROLLER**

Most of industrial applications use PID Controller because of its ease of usage and the simplicity of tuning parameters at the site but we noticed that derivative part sometimes with relative bigger value make the system unstable. The used coefficients for our Controller after many trials with try and error method and Ziegler Nichols method are KP=0.0017, KI=027, and KD=0.

- **FUZZY CONTROLLER**

The error and derivative error of speed are used as the two inputs. Membership functions of input and output variables
have been shown in figure 9 (a),(b). The base rules of obtained fuzzy inference system consist of 25 rules. The fuzzy rules are as shown in table 2.

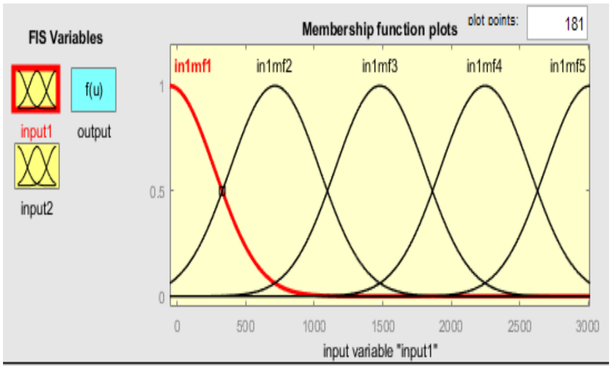

Fig 9 **(a)** Membership functions of speed error input.

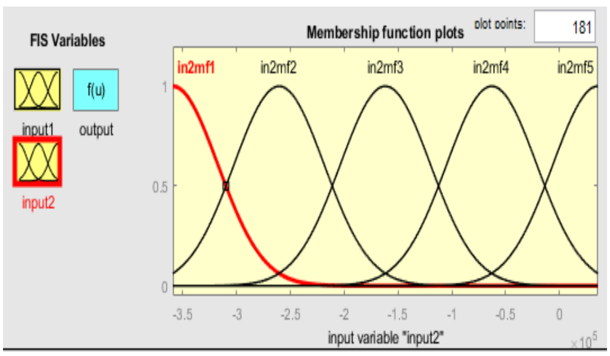

Fig 9 (b) Membership functions of dervative speed error input.

TABLE 2: Fuzzy Rules Matrix

E / dE	LP	MP	SP	Z	SN	MN	LN
LP	**LP**	**LP**	**LP**	**LP**	**MP**	**SP**	**Z**
MP	**LP**	**LP**	**LP**	**MP**	**SP**	**Z**	**SN**
SP	**LP**	**LP**	**MP**	**SP**	**Z**	**SN**	**MN**
Z	**LP**	**MP**	**SP**	**Z**	**SN**	**MN**	**LN**
SN	**MP**	**SP**	**Z**	**SN**	**MN**	**LN**	**LN**
MN	**SP**	**Z**	**SN**	**MN**	**LN**	**LN**	**LN**
LN	**Z**	**SN**	**MN**	**LN**	**LN**	**LN**	**LN**

- **ANFIS CONTROLLER**

As usual at any industry application we need all the time more effective performance with the fastest response, so it was the start of using some intelligent techniques depends on learning like Neuro Fuzzy techniques specially ANFIS (Adaptive Neuro Fuzzy Inference system) which also depends on Fuzzy logic controller and integrating these rules of fuzzy in neural network to make it learning in the system and to improve its performance very fast.
The simulation structure of adaptive neuro fuzzy system with MATLAB is shown in figure .10.

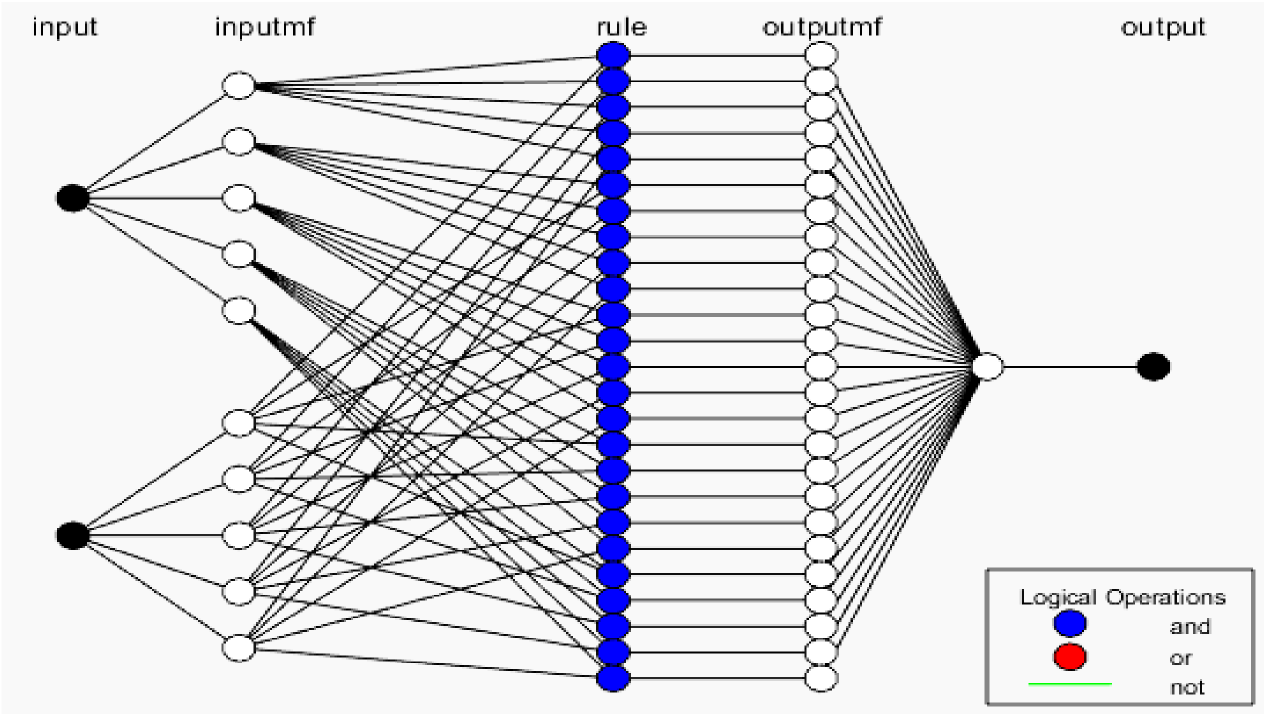

Fig 10. ANFIS structure for speed control of BLDC motor.

VI. RESULTS AND DISCUSSION

The proposed ANFIS technique compared with PI and fuzzy conventional controller can be applied to the system model as shown in figure 8 with reference speed (Nr=3000 r.p.m).

The following figures demonstrate the complex responses of the velocity and the electromagnetic torque (Te) variables with time. It is obvious that the velocity curve with time tends to have a steady state value for three techniques. The electric torque, the stator current curves also decay over time and appear to be negative for the three techniques.

Figure. 11. inicates the response speed with controllers PI, Fuzzy, and ANFIS. It It is apparent that the maximum overshoot curve due to the ANFIS has the zero value. This shows that the ANFIS has high performance relative to the other curves (small settling time and no overshoot).

Figure. 12. demonstrates the electromagnateic torque responses with three techniques. From figure we observe the ANFIS curve has the best damping characteristics compared with other controllers.

Figure. 13. shows the rotor angle responses with three controllers. It is observed that the ANFIS controller has better performance than the PI and fuzzy controllers.

Figure. 14. show back EMF curves with ANFIS for three phases. Maximun and minmum ampltiudes with range (-200 V -200 V) are observed.

Figures. 15-17. show current stator curves for all controllers in three phases. When cleared the ANFIS curves have limited shoots, slowely degrade over time and tend Quickly approaches to zero than other controllers.

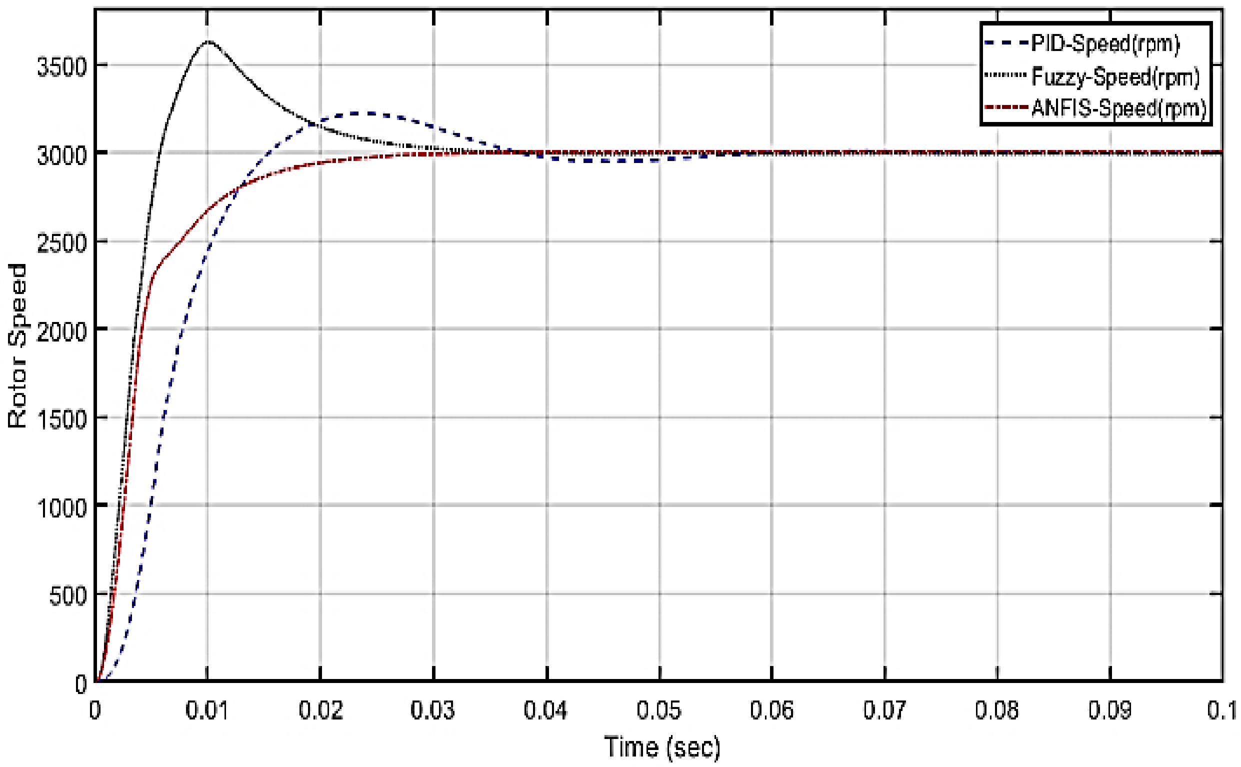

Fig. 11. Speed response of BLDC Motor for all controllers.

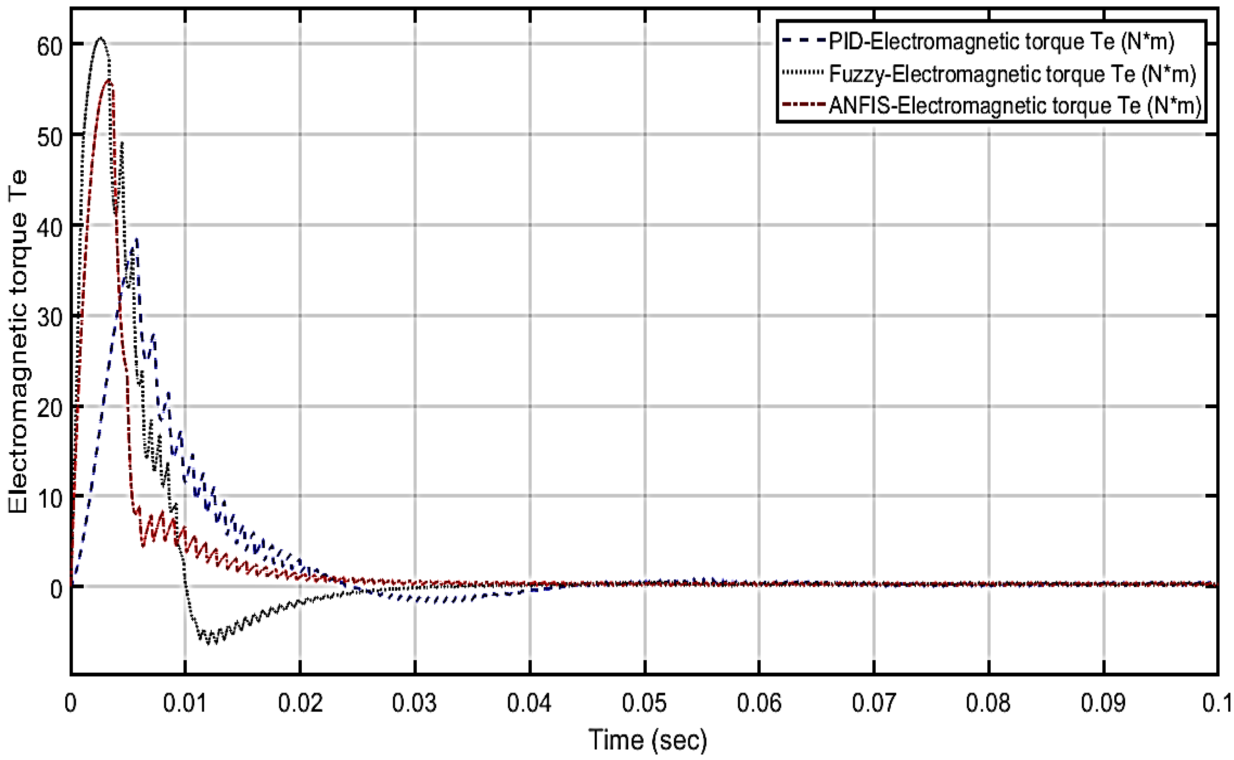

Fig.12. Electromagnateic response of BLDC Motor for all controllers

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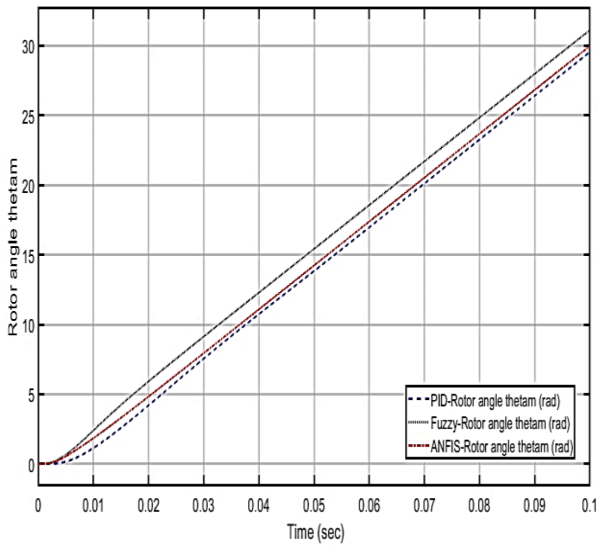

Fig.13 Rotor angle response for all controllers.

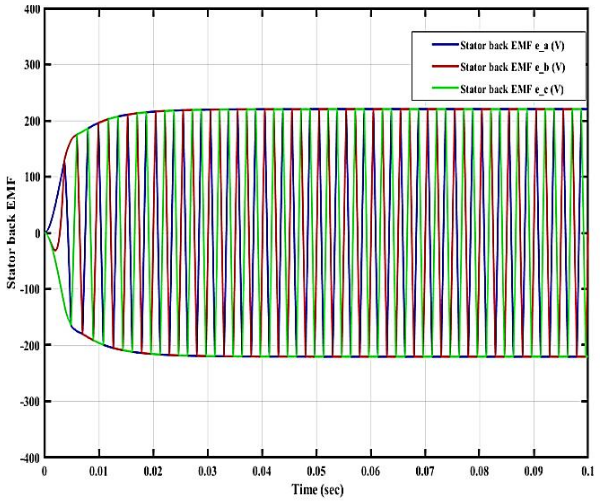

Fig.14 Three phases stator back EMF curves for ANFIS controller.

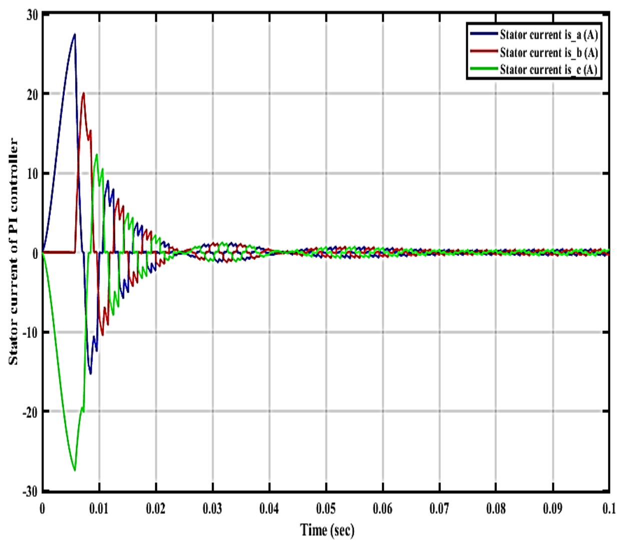

Fig.15. Three phases stator current curves for PI controller.

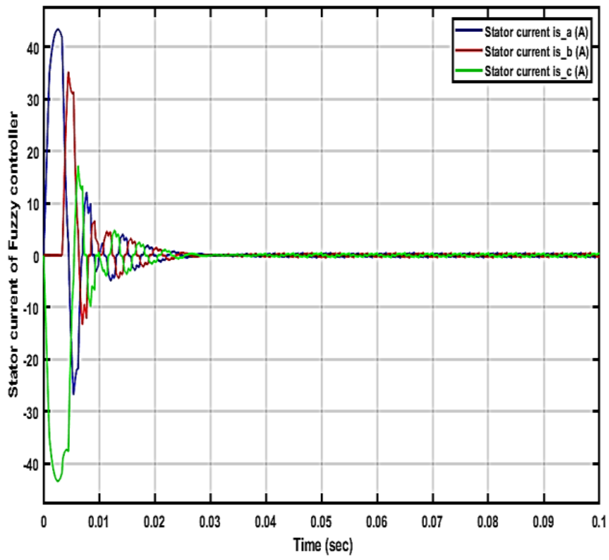

Fig.16. Three phases stator current curves for Fuzzy controller.

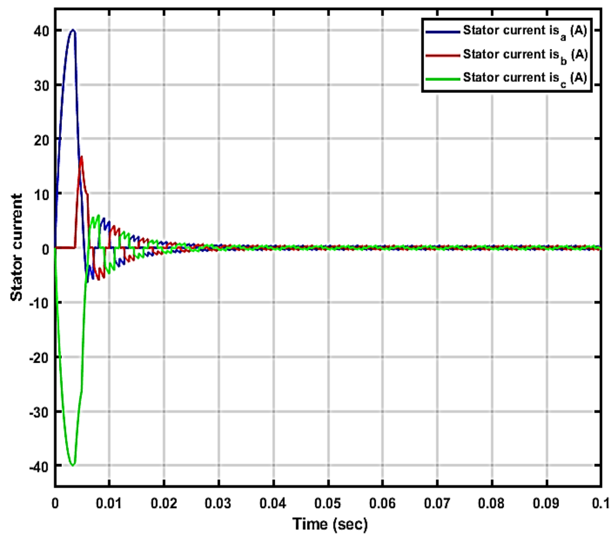

Fig.17. Three phases stator current curves for ANFIS controller.

These figures represent robust stability for the Six-Step Brushless DC Motor Drive system using the proposed ANFIS controller.

The Maximum overshoot and settling time values of speed and electromagnateic torque curves for PI, Fuzzy and ANFIS controllers are listed in Table 3.

It is inferred that the ANFIS controller has high performance compared with PI and Fuzzy controllers from the above figures and statistics in Table 3, respectively.

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TABLE 3

Comparative study for three controllers.

State variable	PI	Fuzzy	ANFIS
Max overshoot Speed	0.0743	0.2091	0
Settling time Speed	0.0654	0.0412	0.0304
Max overshoot(Te)	0.383	0.6066	0.5574
Settlingtime (Te)	0.1	0.0392	0.0379

VII. Hardware and Experimential Results

The following figures 18,19,20 demonstrate the BLDC motor drive , inverter hardware circuits and their expermential results.

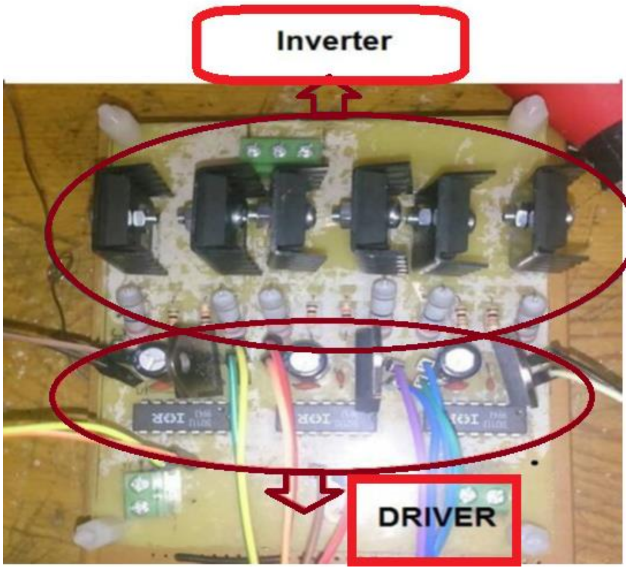

Fig. 18. Implemented hardware circuit

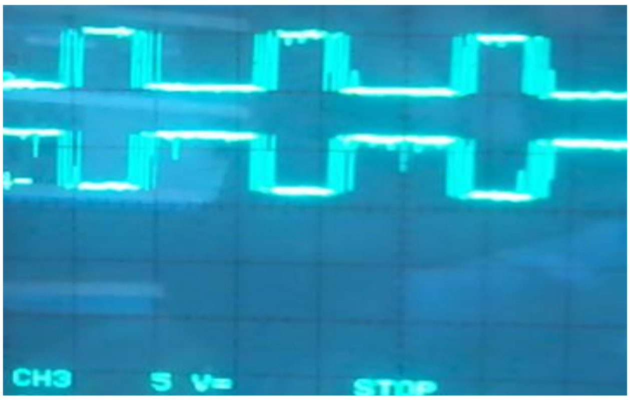

Fig. 19. Pulse generated from the controller unit (5V)

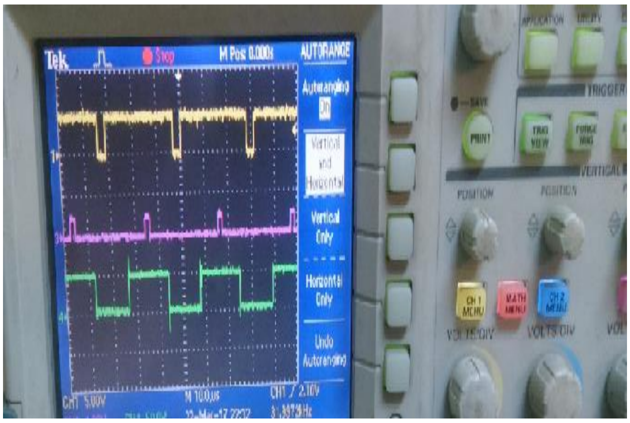

Fig. 20. three phase output with phase shift

VIII. CONCLUSION

This paper introduces a new neuro fuzzy technique for speed modulation of the BLDC Motor. The traditional PI and Fuzzy methods are used to control the state of the motor variables. Type outcomes PI controller has a mild response, Fuzzy controller has a decent response, Neuro Fuzzy controller has a very good response, it has an improvement in time and a fixed time that is higher than PI and Fuzzy controllers. So, we can conclude that Neuro fuzzy controller has a very good performance.

Appendix

TABLE 1
Brushless DC Motor Parameters

Motor Parameters	
Back electromagnetic force	Trapezoidal
Number of pole pairs, P	4
Rated Torque (Nm.)	20
Rated Speed (rpm)	3000
Rated Current (A)	5
Stator phase resistance Rs (ohm)	2.8750
Stator phase inductance Ls (H)	8.5*e-3
Rotor inertia (gcm^2)	0.8e-3
Stator phase, star connections	3
Number of phases	3

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