# ADAPTIVE NEURO-FUZZY SPEED CONTROLLER FOR HYSTERESIS CURRENT CONTROLLED PMBLDC MOTOR DRIVE

V M Varatharaju[1] and B L Mathur[2]

[1] Research Scholar, Department of EEE, Anna University, Chennai, India.
[2] Professor, Department of EEE, SSN College of Engg., Kalavakkam, India.

***ABSTRACT***

*The paper presents a methodology for developing adaptive speed controllers in a permanent-magnet brushless DC (BLDC) motor drive system. A proportional-integral controller is employed in order to obtain the controller parameters at each selected load. The resulting data from PI controller are used to train adaptive neuro-fuzzy inference systems (ANFIS) that could deduce the controller parameters at any other loading condition within the same region of operation. The ANFIS controller is tested at numerous operating conditions with hysteresis current controlled position determination. Paper also provides MATLAB developed PMBLDC motor model and simulation of PI speed controller in comparison with ANFIS controller. The BLDC motor drive system with PI controller exhibits higher overshoot and settling time when compared to the designed ANFIS controller.*

***KEYWORDS***

*PMBLDC Motor, adaptive Speed control, ANFIS.*

## I. INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the permanent magnet brushless dc (PMBLDC) motor has a trapezoidal back emf and requires rectangular stator currents to produce constant torque [1]. The system is becoming increasingly attractive in high-performance variable-speed drives since it can produce torque-speed characteristic similar to that of a permanent-magnet conventional dc motor while avoiding the problems of failure of brushes and mechanical commutation. The PMBLDC motor is becoming popular in various applications because of its high efficiency, high power factor, high torque, simple control and lower maintenance. BLDC motor is one type of synchronous motor, which can be operated in hazardous atmospheric condition and at high speeds due to the absence of brushes.

Pragasan Pillay and R.Krishnan in 1985-1990 [2]-[4] have investigated that the PMSM a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque, while the BLDC motor has a trapezoidal back emf and motor requires rectangular stator current to produce constant torque. Bhim singh, B P singh and K Jain [5] have proposed a digital speed controller for BLDC motor and implemented in a digital signal processor (DSP). Later in 1998, the rotor position and the speed of permanent magnet have been estimated using Extended Kalman filter (EKF) by Peter Vas [6]. Jadric.M and Terzic .B [7] have proposed that the hall effect sensor are usually needed to sense the rotor position which senses the position signal for every 60 degree electrical. The mathematical model of the BLDC motor has been developed and validated in MATLAB platform with proportional-integral (PI) speed controller [8]. Host of efforts has attempted and solved the problem of non linearity and parameter variations of PMBLDC drive [9]-[13].

The draw-backs of Fuzzy Logic Control (FLC) and Artificial Neural Network (NN) can be over come by the use of Adaptive Neuro-Fuzzy Inference System (ANFIS) [18]-[19]. ANFIS is one of the best tradeoff between neural and fuzzy systems, providing: smooth control, due to the FLC interpolation and adaptability, due to the NN back propagation. Some of advantages of ANFIS are model compactness, require smaller size training set and faster convergence than typical feed forward NN. Since both fuzzy and neural systems are universal function approximators, their combination, the hybrid neuro-fuzzy system is also a universal function approximator. The non-linear mapping in a neuro-fuzzy network is obtained by using a fuzzy membership function based neural network.
Using the developed model of the BLDC motor, a detailed simulation and analysis of a BLDC motor speed servo drive is obtained. Closed loop control of PMBLDC motor drive consisting of PI speed controller and hysteresis current controller is simulated and later compared with the ANFIS controller.

## II. MODELLING OF PMBLDC MOTOR

Fig.1 describes the basic building blocks of the PMBLDCM drive. The drive consists of a speed controller, a reference current generator, a pulse width modulated (PWM) current controller, a position sensor, the motor and a current controlled voltage source inverter (CC-VSI). The speed of the motor is compared with its reference value and the speed error is processed in PI speed controller. The output of this controller sets the torque reference. A limit is put on the speed controller output depending on permissible maximum winding currents. The reference current generator block generates the three phase reference currents ($i_a$*, $i_b$*, $i_c$*) using the limited peak current magnitude decided by the controller and the position sensor. In addition to the PI speed controller, a hysteresis controller is employed for current control.

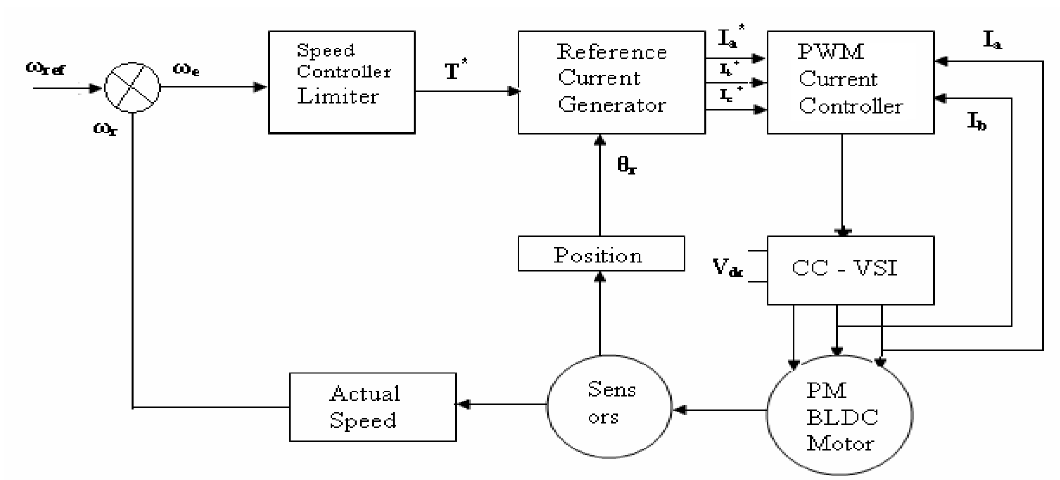


Fig. 1 Block Diagram of PMBLDC Motor Drive

The reference currents have the shape of quasi-square wave in phase with respective back emfs to develop constant unidirectional torque. The PWM current controller regulates the winding currents ($i_a$, ib, ic) within the small band around the reference currents ($i_a$*, ib*, $i_c$*). The motor currents are compared with the reference currents and the switching commands are generated to drive the inverter devices.
The PMBLDC motor is modeled in the three-phase abc frame. The general volt-ampere equation for the circuit shown in the Fig.2 can be expressed as:

$$V_{an} = Ri_a + p\lambda_a + e_{an} \quad (1)$$

$$V_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (2)$$

$$V_{cn} = Ri_c + p\lambda_c + e_{cn} \quad (3)$$

Where, $V_{an}$, $V_{bn}$ and $V_{cn}$ are phase voltages and may be defined as:

$$V_{an} = V_{a0} - V_{n0},$$
$$V_{bn} = V_{b0} - V_{n0}, \text{ and} \quad (4)$$
$$V_{c0} = V_{c0} - V_{n0}.$$

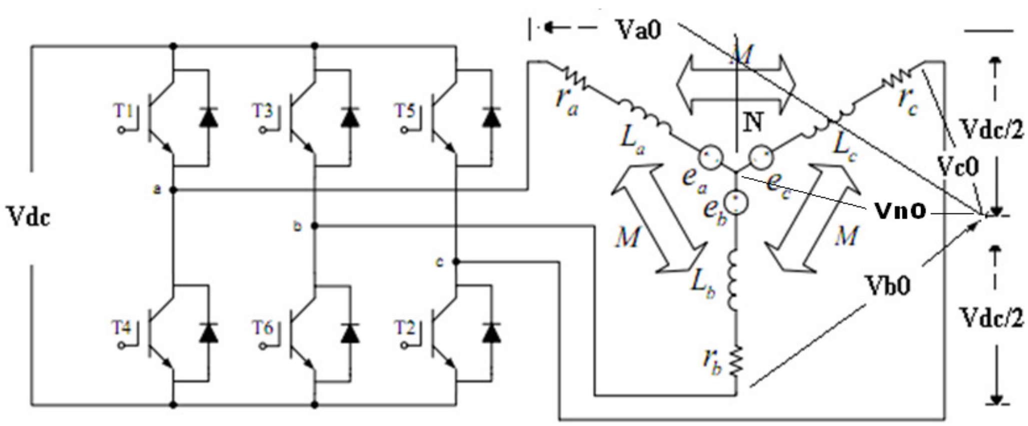


Fig.2 Inverter circuit with PMBLDC motor drive

The phase back emf $e_{an}$ can be expressed as

$$f_a(\theta_r) = E \qquad 0^0 < \theta_r < 120^0$$
$$f_a(\theta_r) = (6E/\pi)(\pi - \theta_r r) - E \qquad 120^0 < \theta_r < 180^0 \quad (5)$$
$$f_a(\theta_r) = -E \qquad 180^0 < \theta_r < 300^0$$
$$f_a(\theta_r) = (6E/\pi)(\theta_r r - 2\pi) + E \qquad 300^0 < \theta_r < 360^0$$

Where, $E = K_b \omega_r$ and $e_{an}$ can be described by E and normalized back emf function $f_a(\theta_r)$ $[e_{an} = E f_a(\theta_r)]$. Where $V_{a0}$, $V_{b0}$, $V_{c0}$ and $V_{n0}$ are three phase and neutral voltages with respect to the zero reference potential at the mid-point of dc link (0) shown in the Fig.2. R is the resistance per phase of the stator winding, p is the time differential operator, and $e_{an}$, $e_{bn}$ and $e_{cn}$ are phase to neutral back emfs. The $\lambda_a$, $\lambda_b$ and $\lambda_c$ are total flux linkage of phase windings a, b and c respectively. Their values can be expressed as:

$$\lambda_a = L_S i_a - M(i_b + i_c) \quad (6)$$
$$\lambda_b = L_S i_b - M(i_a + i_c) \quad (7)$$
$$\lambda_c = L_S i_c - M(i_a + i_b) \quad (8)$$

Where, '$L_s$' and 'M' are self and mutual inductances respectively.

The PMBLDC motor has no neutral connection and hence this results in,

$$i_a + i_b + i_c = 0 \quad (9)$$

Substituting (9) in (6), (7) and (8), the flux linkages are obtained.

$$\lambda_a = i_a(L_S + M),$$
$$\lambda_b = i_b(L_S + M), \text{and} \quad (10)$$
$$\lambda_c = i_c(L_S + M)$$

By substituting (10) in volt-ampere relations (1)-(3) and rearranging these equations in a current derivative of statespace form, gives,

$$pi_a = 1/(L_S + M)(V_{an} - Ri_a - e_{an}) \quad (11)$$

$$pi_b = 1/(L_S + M)(V_{bn} - Ri_b - e_{bn}) \quad (12)$$

$$pi_c = 1/(L_S + M)(V_{cn} - Ri_c - e_{cn}) \quad (13)$$

The developed electromagnetic torque may be expressed as

$$T_e = (e_{an} i_a + e_{bn} i_b + e_{cn} i_c) / \omega_r \quad (14)$$

Where, '$\omega_r$' is the rotor speed in electrical rad/sec. Substituting the back emfs in normalized form, the developed torque is given by

$$T_e = K\{ f_a(\theta_r) i_a + f_b(\theta_r) i_b + f_c(\theta_r) i_c \} \quad (15)$$

The mechanical equation of motion in speed derivative form can be expressed as:

$$p\omega_r = (P/2)(T_e - T_L - B\omega_r)/J \quad (16)$$

Where, 'P' is the number of poles, '$T_L$' is the load torque in N-m, 'B' is the frictional coefficient in Nm/rad, and 'J' is the moment of inertia in kg-m$^2$. The derivative of the rotor position ($\theta_r$) in state space form is expressed as:

$$p\theta_r = \omega_r \quad (17)$$

The potential of the neutral point with respect to the zero potential ($v_{n0}$) is required to be interpreted properly to avoid the imbalance in applied phase voltages.

This can be obtained by substituting (4) in (1) to (3) and adding them together to give

$$\begin{aligned} V_{a0} + V_{b0} + V_{c0} - 3V_{n0} &= R(i_a + i_b + i_c) + \\ (L_S + M)(pi_a + pi_b + pi_c) &+ (e_{an} + e_{bn} + e_{cn}) \end{aligned} \quad (18)$$

Substituting (9) in (18) results in

$$\begin{aligned} &V_{a0} + V_{b0} + V_{c0} - 3V_{n0} = (e_{an} + e_{bn} + e_{cn}) \\ &\Rightarrow V_{n0} = [V_{a0} + V_{b0} + V_{c0} - (e_{an} + e_{bn} + e_{cn})]/3 \end{aligned} \quad (19)$$

The set of differential equations viz. (11),(12), (13), (16) and (19) defines the developed model in terms of the variables $i_a$, $i_b$, $i_c$, $\omega_r$, and $\theta_r$ for the independent variable, time.

# III. SPEED CONTROL

## 3.1 PI Controller

PI controller is widely used in industry due to its ease in design and simple structure. The rotor speed $\omega_{r(n)}$ is compared with the reference speed $\omega_{r(n)}*$ and the resulting error is estimated at the nth sampling instant as :

$$\omega e(n) = \omega r(n)* - \omega r(n) \quad (20)$$

The new value of torque reference is given by:

$$T_{(n)} = T_{(n-1)} + K_p\{\omega_{e(n)} - \omega_{e(n-1)}\} + K_I\{\omega_{e(n)}\} \quad (21)$$

Where $\omega_{e(n-1)}$ is the speed error of previous interval, and $\omega_{e(n)}$ is the speed error of the working interval. $K_p$ and $K_I$ are the gains of PI speed controller. By using Ziegler Nichols method the $K_p$ and $K_I$ values are determined.

## 3.2 ANFIS Controller

In this section basics of ANFIS and development of ANFIS controller are given. ANFIS uses the neural network's ability to classify data and find patterns. It then develops a fuzzy expert system that is more transparent to the user and also less likely to produce memorization error than a neural network. ANFIS keeps the advantages of a fuzzy expert system, while removing (or at least reducing) the need for an expert. The problem with ANFIS design is that large amounts of training data require developing an accurate system. The ANFIS, first introduced by Jang in 1993, is a universal approximator and, as such, is capable of approximating any real continuous function on a compact set to any degree of accuracy [14]-[16]. ANFIS is a method for tuning an existing rule base with a learning algorithm based on a collection of training data. This allows the rule base to adapt.

As a simple example, a fuzzy inference system with two inputs x and y and one output z is assumed. The first-order Sugeno fuzzy model, a typical rule set with two fuzzy If–Then rules can be expressed as [17]:

Rule 1: If x is $A_1$ and y is $B_1$, then $f_1=p_1x+q_1y+r_1$

Rule 2: If x is $A_2$ and y is $B_2$, then $f_2=p_2x+q_2y+r_2$

The resulting Sugeno fuzzy reasoning system is shown in Fig. 3. Here, the output *z* is the weighted average of the individual rules outputs and is itself a crisp value. The corresponding ANFIS architecture is shown in Fig. 4. If the firing strengths of the rules are $w_1$ *and* $w_2$, respectively, for the particular values of the inputs $A_i$ and integral of $B_i$, then the output computed as weighted average,

$$f = \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \tag{22}$$

Let the membership functions of fuzzy sets $A_i$ and $B_i$, are $\mu_{Ai}$ and $\mu_{Bi}$ .

***Layer 1:*** Each neuron "i" in layer 1 is adaptive with a parametric activation function. Its output is the grade of membership function; an example is the generalized bell shape function.

$$\mu(x) = \frac{1}{1 + \left[\frac{x-c}{a}\right]^{2b}} \tag{23}$$

Where [a,b,c] is the parameter set. As the values of the parameters change, the shape of the bell-shape function varies.

***Layer 2:*** .Every node in layer 2 is a fixed node, whose output is the product of all incoming signals.

$$W_i = \mu_{Ai}(x)\,\mu_{Bi}(y),\ i=1,2 \tag{24}$$

***Layer 3:*** This layer normalizes each input with respect to the others (The $i^{th}$ node output is the $i^{th}$ input divided the sum of all the other inputs).

$$\bar{w}_i = \frac{w_i}{w_1 + w_2} \tag{25}$$

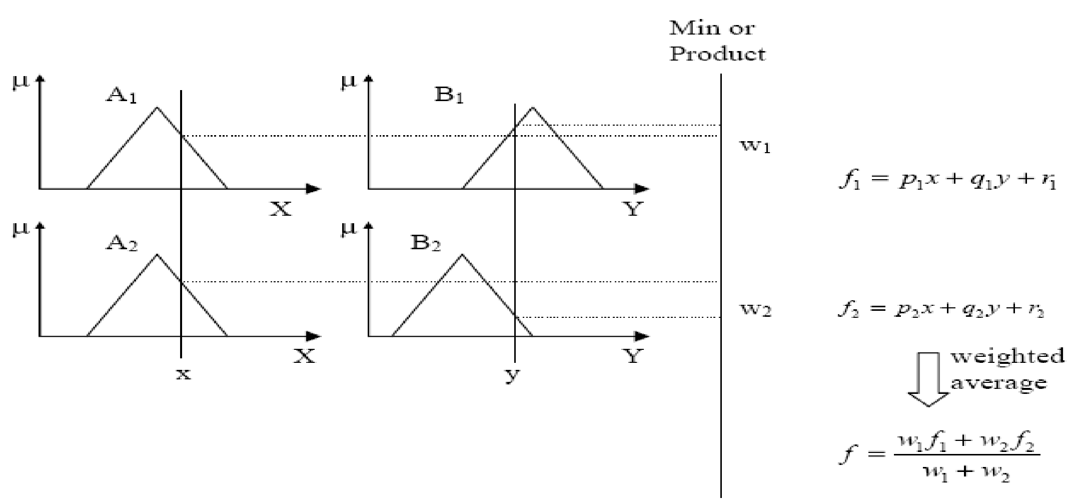


Fig.3 Two-input first-order Sugeno fuzzy model with two rules

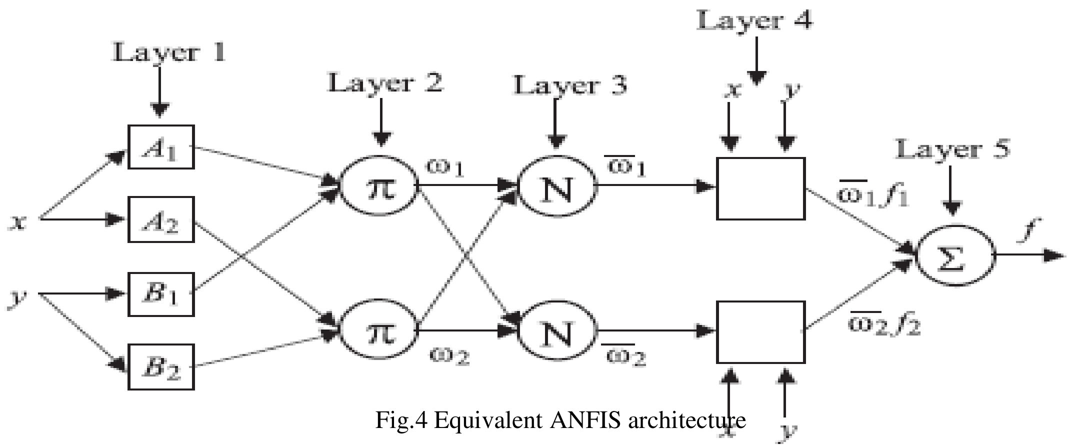


Fig.4 Equivalent ANFIS architecture

***Layer 4:*** This layer's *ith* node output is a linear function of the third layer's *ith* node output and the ANFIS input signals.

$$\bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i) \tag{26}$$

***Layer 5:*** This layer sums all the incoming signals.

$$f = \bar{w}_1 f_1 + \bar{w}_2 f \tag{27}$$

### 3.3 Reference Current Generator

The magnitude of the three phase current (I*) is determined by using reference torque (T*) and the back emf constant ($K_b$) as I* = T* / $K_b$. Depending on the rotor position, the reference current generator block generates three-phase reference currents ($i_a$*, $i_b$*, $i_c$*) by taking the value of reference current magnitude as I*, – I* and zero. The reference current generation is detailed in Table 1.

**Table 1 Reference Current Generation**

| **Rotor Position Signal** | **Reference Currents** | | |
|---|---|---|---|
| | $I_a$* | $I_b$* | $I_c$* |
| 0° - 60° | I* | -I* | 0 |
| 60° - 120° | I* | 0 | -I* |
| 120° - 180° | 0 | I* | -I* |
| 180° - 240° | -I* | I* | 0 |
| 240° - 300° | -I* | 0 | I* |
| 300° - 360° | 0 | -I* | I* |

### 3.4. PWM Current Controller

The PWM current controller contributes to the generation of the switching signals for the inverter devices. The switching logic is formulated as given below.

If $i_a < (i_a^*)$ switch 1 ON and switch 4 OFF

If $i_a > (i_a^*)$ switch 1 OFF and switch 4 ON

If $i_b < (i_b^*)$ switch 3 ON and switch 6 OFF

If $i_b > (i_b^*)$ switch 3 OFF and switch 6 ON

If $i_c < (i_c^*)$ switch 5 ON and switch 2 OFF

If $i_c > (i_c^*)$ switch 5 OFF and switch 2 ON

# IV. SIMULATION RESULTS

In this section the set of equations representing the model of the drive system developed in section 2 is simulated with PI Speed controller. The results are observed for the motor presented in Appendix (3 phase, 2.0 hp, 4- pole 1500 rpm, 4 A) using developed Simulink model in MATLAB. Figure 5-11 show simulated results for the transient and steady state responses for PI controller.

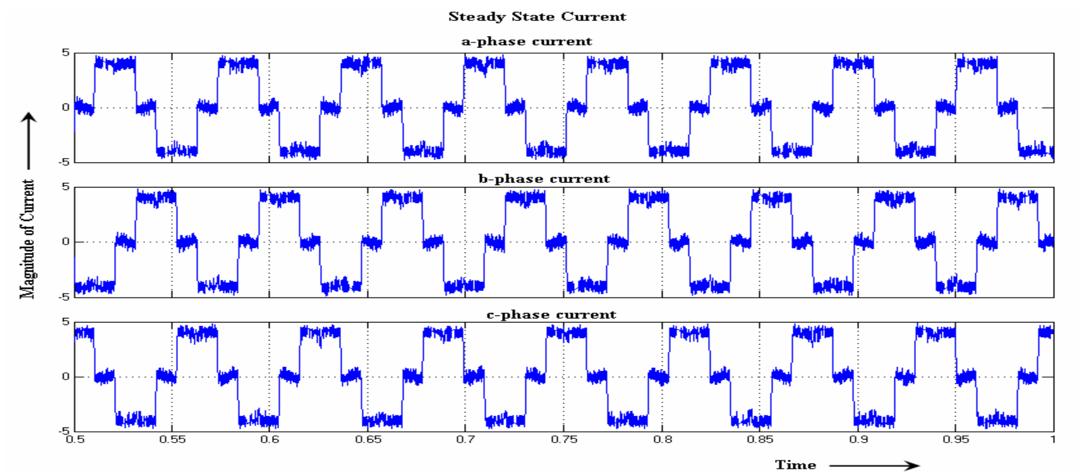


Fig.5 Stator Current of BLDC Motor.

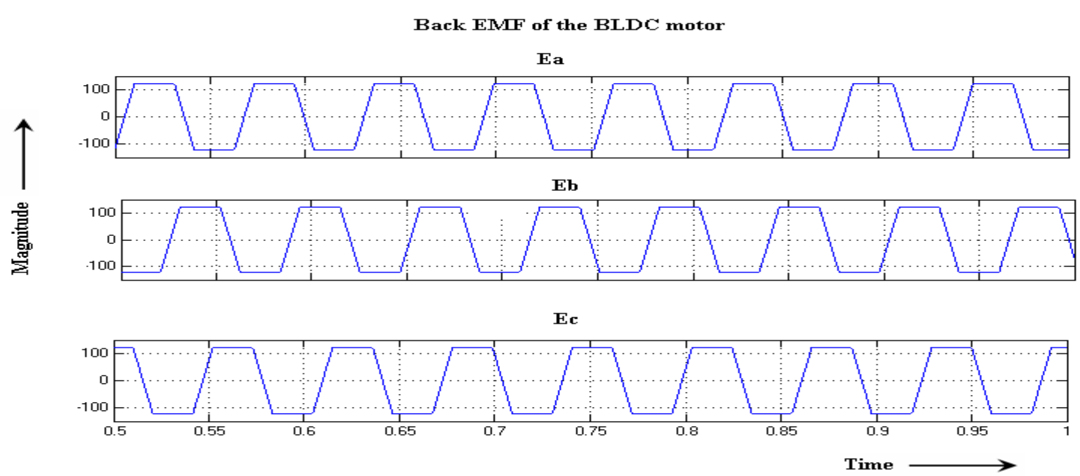


Fig. 6 Trapezoidal back EMF of BLDC Motor

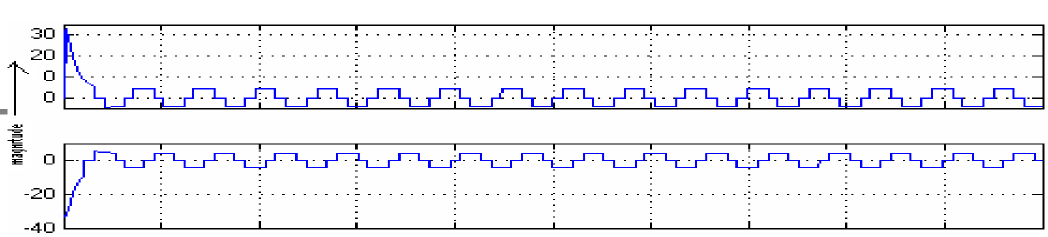

Fig. 7 Reference Current Waveform of BLDC Motor

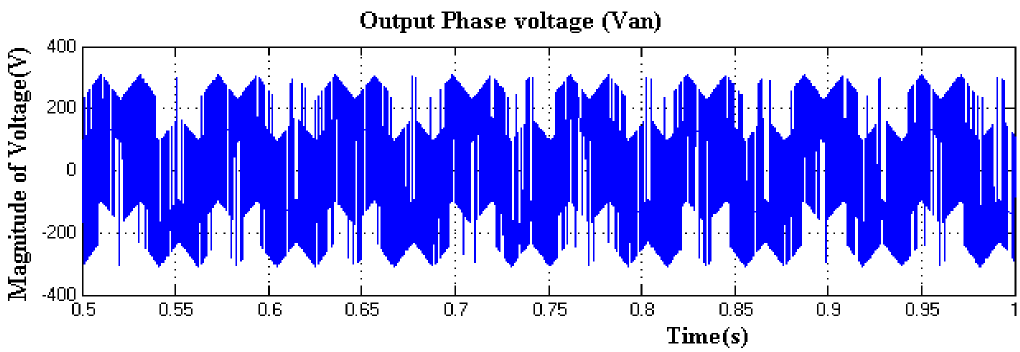


Fig. 8 Phase voltage ($v_{an}$)

The shapes of the simulated current and back emf validate the accuracy of the developed model. In Fig.9 shows the Torque and Speed waveforms for moment of inertia 0.013kg-m$^2$. It reaches the steady state torque and speed suddenly at time 0.03seconds. From these figures it is inferred that increasing the moment of inertia ploys an important role in settling time.

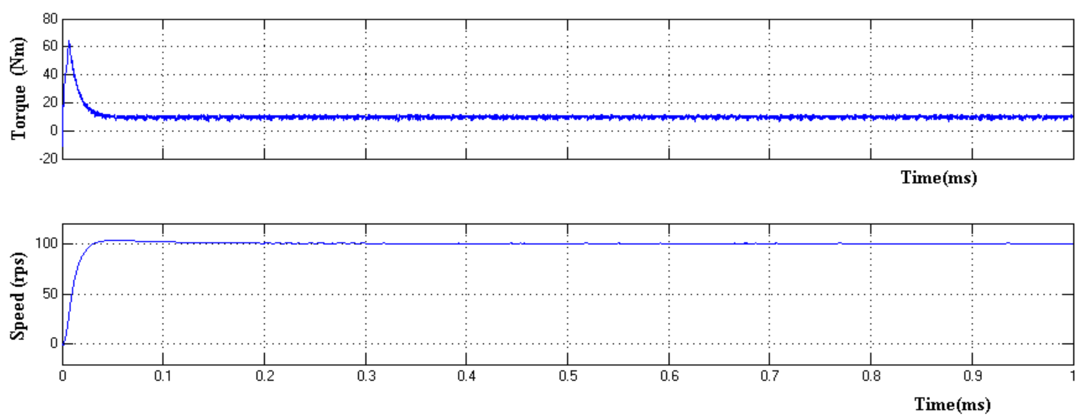


Fig. 9 Torque and Speed Waveforms when moment of inertia =0.013 kg-m$^2$

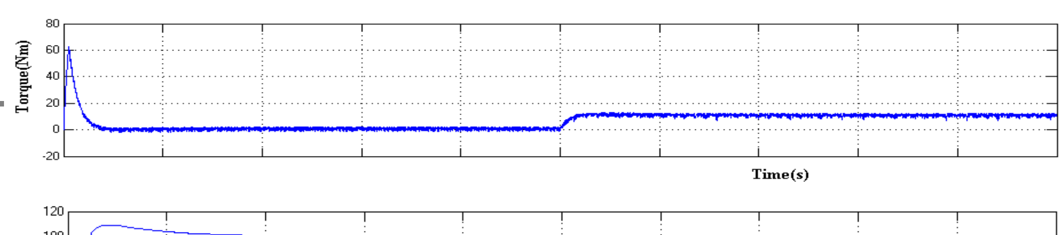

Fig. 10 Torque and speed waveforms for Step Change in Moment of Inertia at 0.5sec.

Fuzzy membership functions can take many forms, but simple straight-line functions are often preferred. Triangular membership functions are often selected for practical applications and different membership functions are tried for the minimum mean root square errors (MRSE). A set of modified membership functions were derived through training the ANFIS by using data obtained from PI controller as illustrated in Fig.11 and Fig.12.

ANFIS controller is designed with two inputs (speed error and change in speed error) and one output and shown in Fig.13. Fig.14 shows the stator currents awhile Fig.15 and Fig.16 show the torque and speed responses respectively for ANSFIS controller.

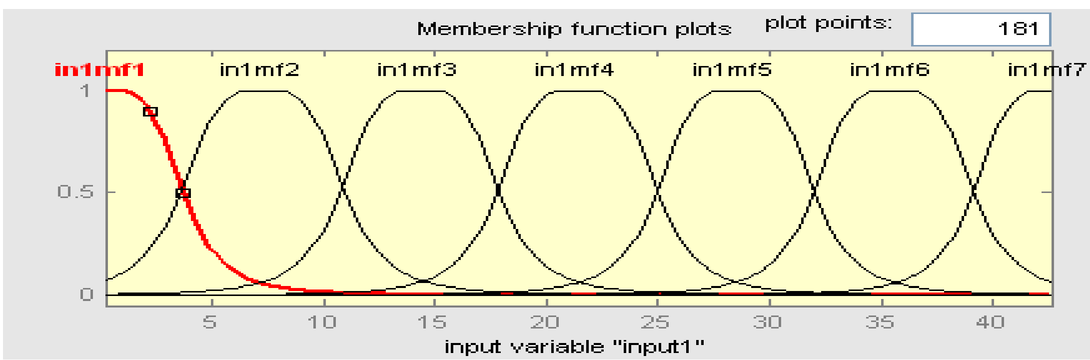


Fig.11. Membership Functions Obtained After Training for Speed Error

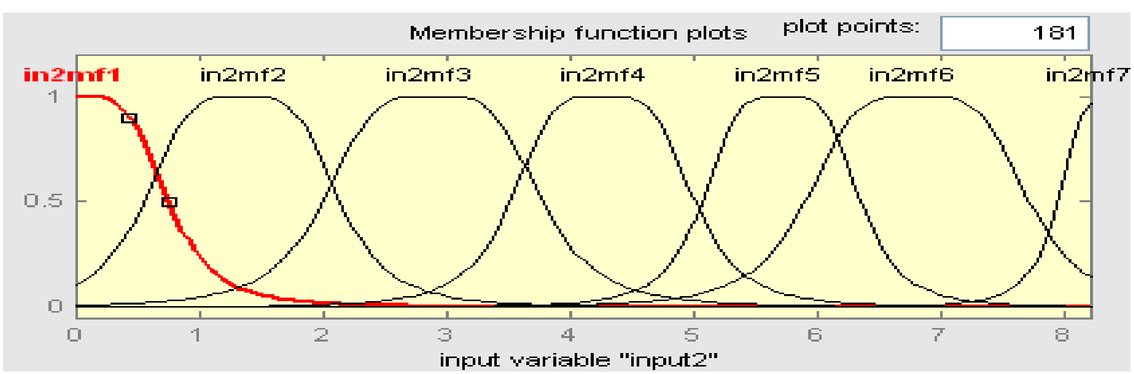


Fig.12. Membership Functions Obtained After Training for Change in Speed Error

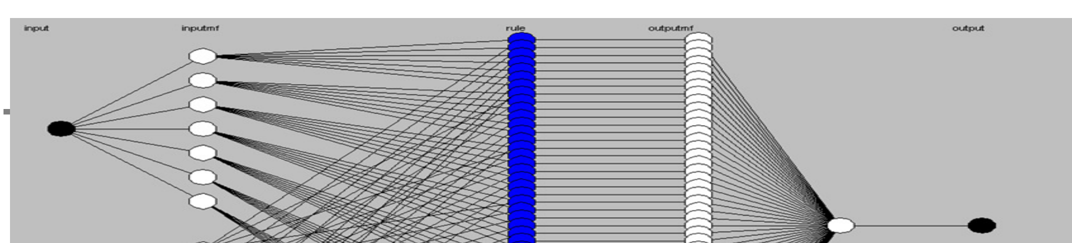

Fig.13. Architecture of ANFIS

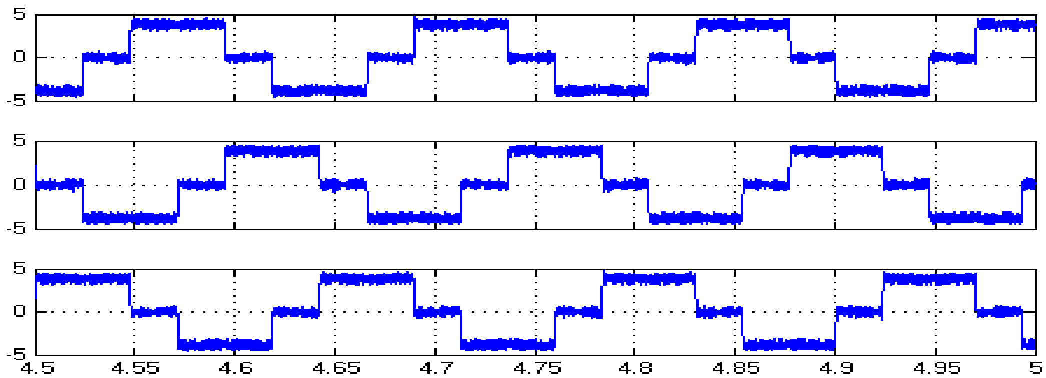


Fig. 14 Stator Current ANFIS controller.

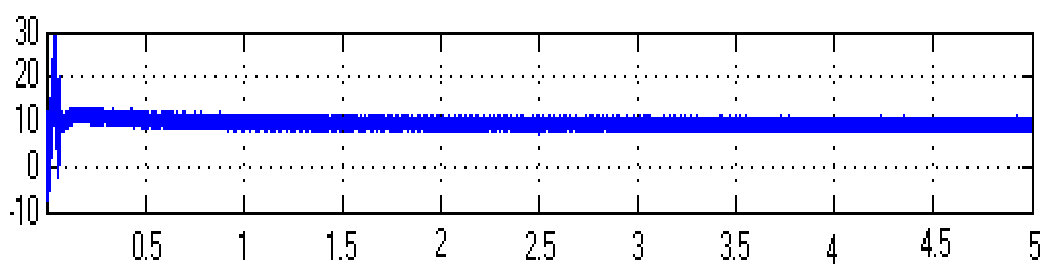


Fig. 15 Torque Response -ANFIS Controller

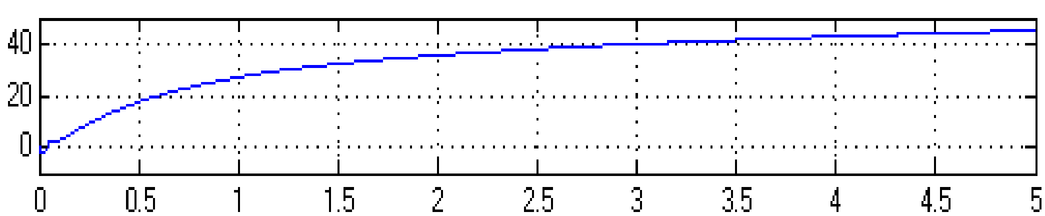


Fig. 15 Speed Response – ANFIS Controller

## V. CONCLUSION

ANFIS served as a basis for constructing a set of fuzzy if-then rules with appropriate membership functions to generate the stipulated input-output pairs. The performance of the developed MATLAB based speed controller of the drive has revealed that the algorithms developed to analyze the behavior of the PMBLDC motor drive system work satisfactorily in software implementation. Using neuro-fuzzy controller error can be reduced and train the membership functions to get the improved speed characteristics. It is found that the ANFIS controller shows reduced overshoot and settling time in both start-up and loaded change conditions and hence robust response.

## REFERENCES

[1] T J E Miller. 'Brushless Permanent Magnet and Reluctance Motor Drives.' Oxford Science Publication, UK, 1989.
[2] P. Pillay and R. Krishnan, "Modeling, simulation and analysis of permanent magnet motor drives-PartI: The permanent magnet synchronous motor drive," this issue, pp. 265-273.
[3] P. Pillay and R. Krishnan, "Modeling, simulation, and analysis of permanent Magnet motor drives. Part II: The brushless dc motor drive," *IEEE Trans. Ind. Appl.*, vol. IA-25, no. 2, pp. 274–279, Mar./Apr. 1989.
[4] R.Krishnan and A.J. Beutler, "Performance and design of an axial field permanent magnet synchronous motor servo drive," in Proc.IEEE IAS Annual Meeting,pp. 634-640,1985.
[5] Bhim singh, B P Singh and (Ms) K Jain, "Implementation of DSP Based Digital Speed Controller for Permanent Magnet Brushless dc Motor", *Proc. IE(I) Journa*l-EL'2002.
[6] Peter Vas, "Sensorless Vector and Direct Torque Control", Oxford University press, 1998.
[7] M.Jadric and B.Terzic, "Design and Implementation of the Extended Kalman filter for the speed and rotor position estimation of Brushless motor." *Proc IEEE'2001*, vol.48. no.3, 2001.
[8] V.M.Varatharaju, B.L.Mathur and K. Udhyakumar, "Comprehensive Model of a Trapezoidal PMBLDC Motor and Drive System Performance with PI Speed Controller" *AMSE periodicals of Modeling, Measurement and Control, (In Press),* 2011.
[9] M. Lajoie-Mazenc, C.Villanueva, and J.Hector, "Study and implementation of a hysteresis controlled inverter on a permanent magnet synchronous machine," *IEEE Trans. Industry Applications*, vol. IA-21, no.2, pp. 408-413, Mar./Apr. 1985.
[10] T Sebastian and G R Slemon. 'Transient Modeling and Performance of Variable Speed Permanent Magnet Motors.' *IEEE Transactions on IA*, vol 25, no 1, January/February 1989, p 101.
[11] A Rubai and R C Yalamanchi. 'Dynamic Study of an Electronically Brushless dc Machine via Computer Simulations.' *IEEE Transactions on EC*, vol.7, no 1, March 1992, p 132.
[12] P C K Luk and C K Lee. 'Efficient Modeling for a Brushless dc Motor Drive.' *Conference Record of IEEE-IECON*, 1994, p 188.
[13] T.S.Radwan,SMIEEE,M.M.Gouda, "Intelligent Speed control of Permanent Magnet Synchronous Motor Drive Based-on Neuro-Fuzzy Approach", *Proceedings of IEEE Power Electronics and drive Systems Conference (PEDS-05)*, 2005.
[14] Jang, J, S.R. ANFIS: adaptive-network-based fuzzy inference system. *IEEE Trans. Sys. Manage. and Cybernetics* 23(3), 665–685, 1993.
[15] Jain, S. K., Das, D. & Srivastava, D. K., "Application of ANN for reservoir inflow prediction and operation" *J. Water Resour. Plan. Manage. ASCE* 125 (5), 263–271, 1999.
[16] Jang, J.-S.R., Sun, C.-T & Mizutani, E. (1997) *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligance*. Prentice Hall, Upper Saddle River, New Jersey, USA, 1997.
[17] Ozgur Kisi, "Suspended sediment estimation using neuro-fuzzy and neural network approaches", *Hydrological Sciences–Journal–des Sciences Hydrologiques,* 50 (4), pp. 683-696, August 2005.
[18] Zhi Rui Huang and M.N. Uddin, "Development of a simplified Neuro- Fuzzy controller for an IM drive," in the Proc. of IEEE International Conf. on Industrial Technology 2006 , 15-17 Dec. 2006, pp. 63–68.
[19] M. N. Uddin Z. R. Huang and Md. M. Chy "A simplified self-tuned neuro-fuzzy controller based speed control of induction motor drives," in the Proc. Of PES General Meeting 2007, 24-28 June. 2007, pp. 1–8.

## APPENDIX

| | |
|---|---|
| Rating: | 2.0 hp |
| Number of Poles: | 4 |
| Type of connection: | Star |
| Rated speed: | 1500 rpm |
| Rated current: | 4A |
| Resistance/phase: | 2.8 Ω |

Back EMF constant: 1.23V sec/rad
Inductance (Ls + M): 0.00521 H/phase
Moment of Inertia: 0.013 Kg-$m^2$

**Authors**

**V M Varatharaju** received the B.E. degree in electrical and electronics engineering from Madras University, Chennai, India, in 1998, the M.E. degree in power systems from Annamalai University, Chidambaram, India in 2002; and presently he is a research scholar in electrical engineering department in College of Engineering, Anna University, Chennai, India His areas of interest include power system control, power electronics application to power systems and electrical machines.

**B.L. Mathur** received his B.E (EE) degree first class from Rajasthan University, M.Tech. Power systems from the Indian Institute of Technology Bombay and Ph.D from the Indian Institute of Science, Bangalore. Professor in the Department of Electrical and Electronics Engineering has 47 years of teaching and research experience. His Ph.D thesis was adjudged to be the best thesis of the year 1979 for Application to Industry and was awarded GOLD MEDAL by I.I.Sc. He has published over 150 research publications in refereed international journals and in proceedings of international conferences. He has completed three AICTE funded projects worth Rs. 5 lakhs, 7 lakhs and 20 lakhs and two projects funded by SSN Trust worth Rs. 1.5 lakhs. He is a recognized supervisor of Anna University Chennai, Anna University of Technology and Sathyabama University Chennai. Two of his students have been awarded Ph.D. in the year 2010 and seven others are pursuing research under his supervision. The subjects on whom the scholars are working/worked under his supervision are: Solar energy systems, Wind energy systems, Protection of transformers, Multi-level inverters, Magnetic Levitation and Brushless D.C. motor.