Torque Control of BLDC Motor using ANFIS Controller

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Abstract— In this paper, A novel design of an adaptive neuro fuzzy inference system(ANFIS) for controlling some of the parameters, such as speed, torque, flux, voltage, current, etc. of the brushless dc motor is presented.. exact quickened torque control for a brushless dc motor (BLDCM) is accomplished by electromagnetic torque control and influence torque concealment. To start with, the electromagnetic torque ripple is diminished in commutation and conduction areas. In previous case, the ripple is smothered by covering recompense control and improving the obligation proportion of the dynamic controller. In recent, the unbalance ripple caused by the uneven three phase windings is diminished by the proposed asymmetry compensation capacity, the aggravation ripple made by the back electromotive power (EMF) is repaid by feed forward control. Second, the aggravation torque has been observed and compensated through the unsettling influence torque controller whose compensation coefficient is acquired by line-to-line back EMF coefficient estimation. In order to verify the effectiveness of the controller, the simulation results are compared with PI controller. The simulation result show that the overall performance of ANFIS based BLDC motor is much better when compared to PI controller under different operating conditions

Key words: Quickened Torque, Brushless Dc Motor (BLDCM), Influence Torque, Electromagnetic Torque, Aggravation, Torque Ripple

I. INTRODUCTION

It is well known that brushless dc motor (BLDCM) has received widespread acceptance in industrial applications. Many machine and control schemes have been developed to improve the performance of BLDC motor drives. Some simulation models based on state-space equations, Fourier-transforms, d-q axis model and variable sampling have been proposed for the analysis of BLDC motor drives. Limitations of brushed DC motors overcome by BLDC motors include lower efficiency and susceptibility of the commutator assembly to mechanical wear and consequent need for servicing, BLDC motors offer better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges [1]. Due to their favorable electrical and mechanical properties, BLDC motors are widely used in servo applications such as automotive, aerospace, medical, instrumentation, actuation, robotics, machine tools and industrial automation equipment. Many machine design and control schemes have been developed to improve the performance of BLDC motor drives. The model of motor drive has to be known in order to implement an effective control in simulation. Furthermore the fuzzy logic controllers have been used to analyse BLDC motor drive [2]. A comprehensive model with MATLAB/fuzzy logic toolbox is used to design the FLC, which is integrated into simulations with simulink is analyzed

The relationship between the quickened torque and electromagnetic torque is portrayed as:

$$T_o = T_e - T_l \qquad (1)$$

Where to is the quickened torque or flywheel torque, and Te is the electromagnetic torque.

II. SETUP OF THE BLDCM CONTROL SYSTEM

A. System Configuration:

The proposed quickened torque control block diagram is shown in Fig. 1. It essentially comprises of an electromagnetic torque controller and an unsettling influence torque controller. To start with, ripple free electromagnetic torque control is actualized through compensation and conduction current controllers. Second, the unsettling influence torque is evaluated by increasing speed based DOB and repaid through the reciprocal of torque coefficient which differs with rotor position.

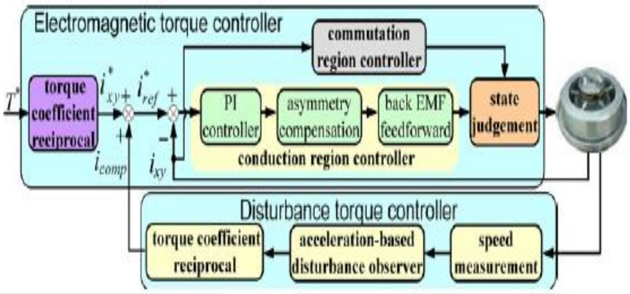

Fig. 1: Quickend torque control scheme block diagram.

B. Drive System Model:

The phase current and torque ripples are serious for the small inductance BLDCM, when the three-phase inverter is modulated. A torque ripple minimization technique has been proposed by a buck converter in the front of the three-phase inverter[3].The buck converter-based BLDCM drive framework as indicated in Fig.2.

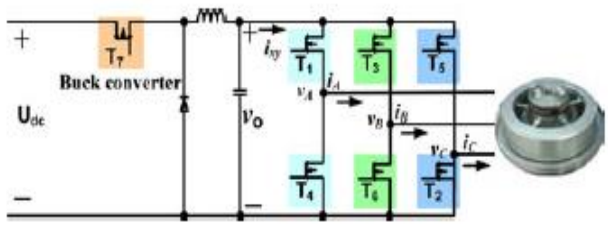

Fig. 2: Buck converter-based BLDCM drive system block diagram.

The BLDCM voltage comparison of three phase windings is

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \frac{d}{dt} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} v_{N0} \\ v_{N0} \\ v_{N0} \end{bmatrix} \qquad (2)$$

where Va, Vb, and Vc are the phase-winding terminal-to-ground voltages; i_a, i_b and i_c are the phase-

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winding currents; e_a, e_b,and e_c are the line-to-neutral back EMFs; v_{N0} is the neutral point-to-ground voltage; R_a, R_b, and R_c are phase-winding resistances; and L_a, L_b, and Lc are the phase-winding inductances respectively.

III. ELECTROMAGNETIC TORQUE CONTROL

The electromagnetic torque Te can be communicated as

$$T_e = \frac{e_a(\theta_a)i_a+e_b(\theta_b)i_c+e_c(\theta_c)i_c}{w_m} \quad (3)$$

where θ is the rotor position, ω is the rotor speed, the subscripts "e" and "m" indicate the electrical quantity and mechanical quality, individually.

At the point when a solitary dc-link current sensor is used in the two phase switching mode, the electromagnetic torque in non commutation area can be inferred as

$$T_e=\frac{e_x(\theta_x)i_x+e_y(\theta_y)i_y}{w_m} = \frac{e_{xy}(\theta_e)i_{xy}}{w_m} = k_{xy}(\theta_e)i_{xy} \quad (4)$$

Where the subscripts "x" and "y" denotes the conduction phases,$e_{xy}(\theta e)$ is the line-to-line back EMF, i_{xy} is the dc-link current, $k_{xy}(\theta e)$ is the torque coefficient, i.e., line-to-line back EMF coefficient.

A. *Torque Coefficient Acquirement:*

The torque coefficient can be acquired through line-to-line back EMF coefficient estimation. The line-to-line back EMFs can be ascertained from rotor velocity utilizing shape works and depicted as

$$e_{xy}(\theta_e) = f_{xy}(\theta_e) \times w_m \quad (5)$$

Where $f_{xy}(\theta_e)$ is line-to-line back EMF shape capacity.

Consequently, the electromagnetic torque can be figured agreeing to the line-to-line back EMF shape capacities and dc-link current as follows

$$i^*_{xy} = \frac{T^*}{\hat{k}_{xy}(\hat{\theta}_e)} \quad (6)$$

Where T^* is the reference torque, superscripts "∧" and "∗" mean the estimated and reference values, separately. Where $\hat{k}_{xy}(\hat{\theta}e)$=$\hat{f}_{xy}(\hat{\theta}e)$

B. *Electromagnetic Torque/DC-Link Current Ripple Reduction:*

The ripple is primarily made out of commutation region and conduction region ripple. There are three principle wellsprings of conduction region ripple generation in the little inductance BLDCM: modulation ripple, unbalance ripple, and disturbance ripple.

1) *Commutation Ripple Reduction:*

As the compensation term is short for the small inductance motor, ordinary compensation control plans won't work, the commutation point-to-ground voltage v_{N0} can be derived as

$$v_{N0} = \frac{1}{3}(v_a + v_b + v_c - e_a - e_b - e_c) \quad (7)$$

Utilizing phase A as the noncommutation phase, phase B as the active phase, and phase C as the approaching stage, the phase currents are determined as

$$\begin{aligned} i_a &=(i_{ab} - \frac{v_{a0}}{R_a}) \exp\left(-\frac{R_a}{L_a}t\right) + \frac{v_{a0}}{R_a} \\ i_b &=(-i_{ab} - \frac{v_{b0}}{R_a}) \exp\left(-\frac{R_b}{L_b}t\right) + \frac{v_{a0}}{R_b} \quad (8) \\ i_c &=(-\frac{v_{c0}}{R_c}) \exp\left(-\frac{R_c}{L_c}t\right) + \frac{v_{c0}}{R_c} \end{aligned}$$

Where i_{ab} is the dc-link current before commutation. The falling time of active stage and rising time of approaching stage can be ascertained as

$$\begin{aligned} t_{B\_fall} &= -\frac{L_b}{R_b}\ln\left(\frac{v_{b0}}{i_{ab}R_b + v_{b0}}\right) \\ t_{C\_rise} &= -\frac{L_c}{R_c}\ln\left(1 + \frac{i_{ab}R_c}{v_{c0}}\right) \quad (9) \end{aligned}$$

2) *Conduction Region Ripple Reduction:*

The ordinary ripple control methodologies focus on compensation ripple reduction, which can function admirably with the general system. The transfer function of the present PI controller is denoted as

$$G_c(s) = \frac{i_{xy}(s)}{i^*_{xy}(s)} = \frac{k_{pc}s+k_{ic}}{L_{xy}x^2+(k_{pc}+R_{xy})s+k_{ic}} \quad (10)$$

Where K_{pc} and K_{ic} are the PI additions, R_{xy} and L_{xy} are line winding resistance and inductance, individually. Accepting that phase x and phase y are directed in the two-phase exchanging mode, as indicated by the phase voltage mathematical statement the three-stage inverter terminal voltage mathematical statement can be communicated as

$$v_0 = R_{xy}i_{xy} + L_{xy}\frac{di_{xy}}{dt} + e_{xy} \quad (11)$$

The obscure parameters α and β are characterized as follows:

$$\begin{aligned} \alpha &= \exp(-R_{xy}Ts/L_{xy}) \quad (12) \\ \beta &= (1-\alpha)/R_{xy} \end{aligned}$$

Where Ts is sampling time. Assuming that the aggravation voltage e_{xy} is completely adjusted, so that the system model is simplified, and a simple observer can built to estimate the dc link current is given by

$$i_{xy}(k) = \alpha i_{xy}(k-1) + \beta v^*_0(\text{k-1}) \quad (13)$$

where $\hat{v}^*_0(k) = v_0(k) - \hat{e}_{xy}(k)$

The obscure parameters α and β can be assessed [5] and [6]. Therefore, through the state observer, α and β can be assessed progressively, the line-winding resistance R_{xy} and inductance L_{xy} can be calculated from equation (14)

$$\begin{aligned} R_{xy} &=(1-\alpha)/\beta \quad (14) \\ L_{xy} &= -R_xT_s/\ln(\alpha) \end{aligned}$$

As the winding inductance is very small, the resistance plays the main role in phase current waveform. An asymmetry compensation function is proposed to solve the unbalanced problem, Accepting that the output of current PI controller is uc, therefore the control effort given by asymmetry remuneration capacity can be portrayed as

$$u_R = f(\hat{R}_{xy}) \times u_c \quad (15)$$

Moreover, the unsettling influence voltage can be adjusted through feed forward control. Thus, the output of conduction current controller can be given as

$$u_e = f\left(\hat{R}_{xy}\right) \times u_c + \hat{e}_{xy} \quad (16)$$

Thus, the enhanced electromagnetic torque execution can be acquired with the assistance of torque coefficient estimation and dc-link current control.

IV. ANFIS CONTROLLER

ANFIS is a based on fuzzy inference system and this system uses the given input and output data to build fuzzy inference system. First a training data set that contains the desired input/output data pairs of target systems to be modeled is required. The design parameters required for any ANFIS controller are number of data pairs, training data sets and checking data sets. For training the number of epochs to be chosen to start the training, learning results to be verified after mentioning the step size. Then the designed ANFIS has two inputs namely, the actual motor speed and reference

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speed while the output is the torque, which is used to generate current. Structure of ANFIS speed controller is shown in Fig.3 it is based on the three-layer feed forward fuzzy neural network.it contains five layers namely

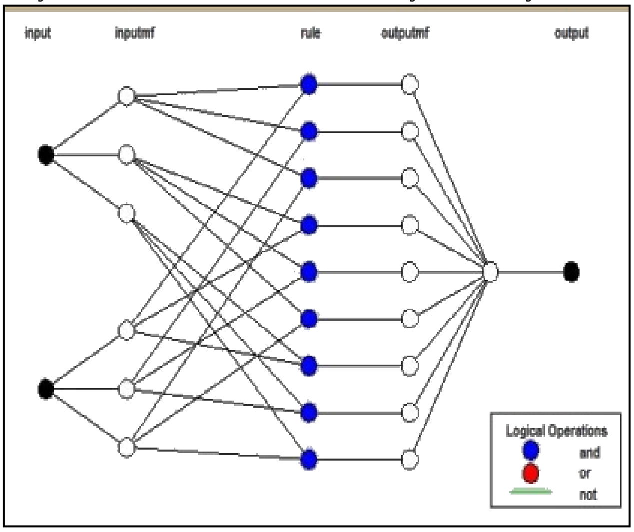

Fig. 3: Structure of ANFIS controller

A. Layer 1: (InputLayer)

Input layer represents input variables of controller, they are actual speed and reference speed respectively. This layer just supplies the input values x_i to the next layer, where i= 1 to n

B. Layer 2: (Fuzzification Layer)

This layer receives the input values from the first layer it creates membership function for the respective input variables and these are inputs to the next layer

C. Layer 3: (Rule Layer)

Each node (each neuron) in this layer performs the pre-condition matching of the fuzzy rules, i.e., they compute the activation level of each rule, the number of layers being equal to the number of fuzzy rules. Each node of these layers calculates the correction which are normalized.

D. Layer 4: (Defuzzification Layer)

It provides the output values "y" resulting from the inference of rules. Connections between the layers l 3 & l 4 are weighted by the fuzzy rules that represent another set of parameters for the neuro fuzzy network.

E. Layer5: (Output Layer)

In this layer all the inputs coming from the layer 4 sums up and transforms the fuzzy classification results into a crisp values.

To start with, we design the controller using the ANFIS scheme. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as large or small), may be represented by the fuzzy sets. Fuzzy set is an extension of a 'crisp' set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow partial membership, which means that an element may partially belong to more than one set.

Our basic structure of the developed ANFIS coordination controller to control the torque of the BLDCM consists of 4 important parts, viz., fuzzification, knowledge base, neural network and the de-fuzzification blocks,

The inputs to the ANFIS controller, i.e., the error & the change in error is modeled using the Eq. (17) as

$$e(k) = w_{ref} - w_r, \qquad (17)$$

$$\Delta e(k) = e(k) - e(k-1)$$

Where w_{ref} is the reference speed, w_r is the actual rotor speed, e(k) is the error and Δe(k) is the change in error.

The fuzzification unit converts the crisp data into linguistic variables, which is given as inputs to the rule based block. The set of 9 rules are written on the basis of previous knowledge / experiences in the rule based block. The rule base block is connected to the neural network block. Back propagation algorithm is used to train the neural network to select the proper set of rule base. For developing the control signal, the training is a very important step in the selection of the proper rule base. Once the proper rules are selected & fired, the control signal required to obtain the optimal outputs is generated. the output of the NN unit is given as input to the de-fuzzification unit and the linguistic variables are converted back into the numeric form of data in the crisp form.

In the fuzzification process, i.e., in the first stage, the crisp variables, the speed error & the change in error are converted into fuzzy variables or the linguistics variables. The fuzzification maps the 2 input variables to linguistic labels of the fuzzy sets.The fuzzy coordinated controller uses the linguistic labels. Each fuzzy label has an associated membership function. The membership function of triangular type is used in our work. The inputs are fuzzified using the fuzzy sets & are given as input to ANFIS controller. The rule base for selection of proper rules using the back propagation algorithm is written as shown in the table I.

e de	NE	ZE	PS
NE	NE	NE	NE
ZE	ZE	ZE	ZE
PS	PS	PS	PS

Table 1: rule base for controlling the speed

The developed fuzzy rules (3×3) = 9 included in the ANFIS controller is given below in the form of an algorithm as follows:

- If (e is ne) and (de is ne) then (T is ne) (1)
- If (e is ne) and (de is ze) then (T is ze) (1)
- If (e is ne) and (de is ps) then (T is ps) (1)
- If (e is ze) and (de is ne) then (T is ne) (1)
- If (e is ze) and (de is ze) then (T is ze) (1)
- If (e is ze) and (de is ps) then (T is ps) (1)
- If (e is ps) and (de is ne) then (T is ne) (1)
- If (e is ps) and (de is ze) then (T is ze) (1)
- If (e is ps) and (de is ps) then (T is ps) (1)

Simulink diagram for the speed and torque of BLDC motor by using ANFIS controller is given as shown in figure 4

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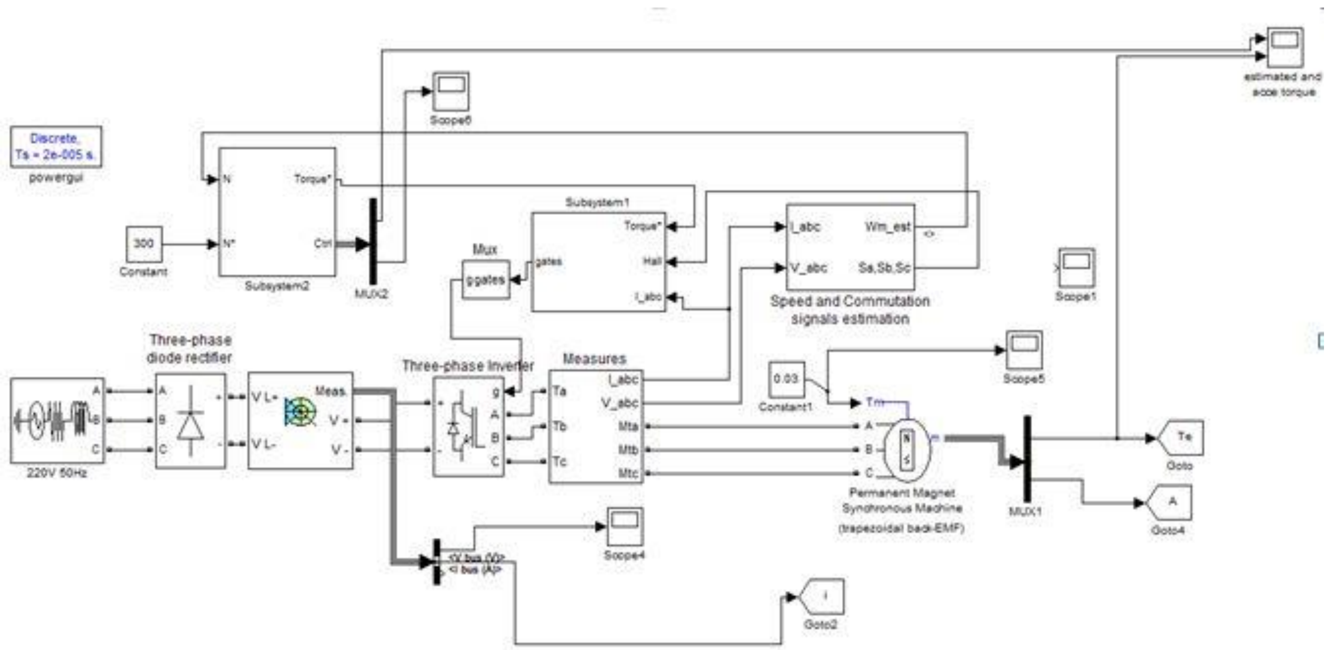

Fig. 4: Simulink diagram for speed and torque of BLDC motor by using ANFIS controller

V. Simulation Results

A. Sudden DC-link drop:

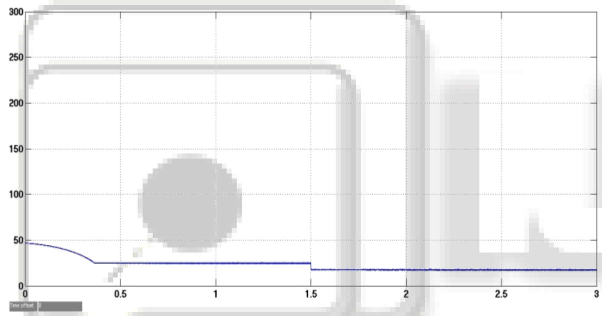

Fig. 5: Inverter bus voltage of BLDC motor by using PI controller

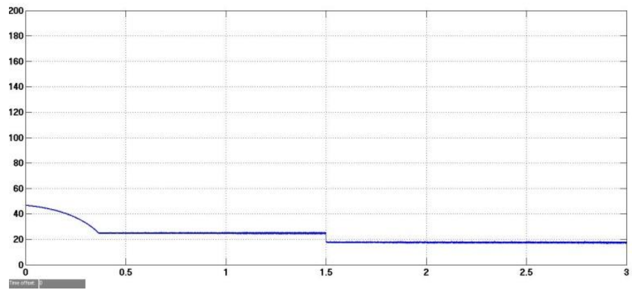

Fig. 6: Inverter bus voltage of BLDC motor by using ANFIS controller

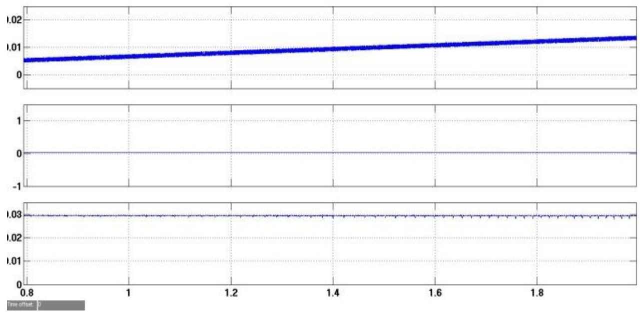

Fig. 7: Performance of torque during sudden change in DC link drop by using PI controller

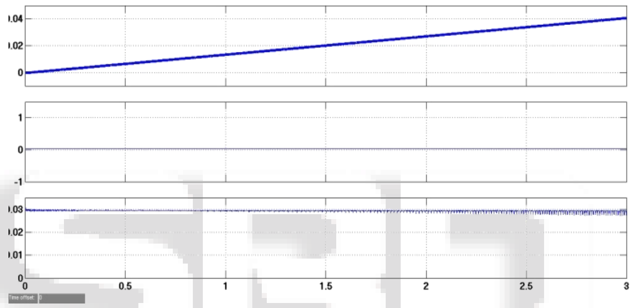

Fig. 8: Performance of torque during sudden change in DC link drop by using ANFIS controller

B. Sudden Reference Torque Change:

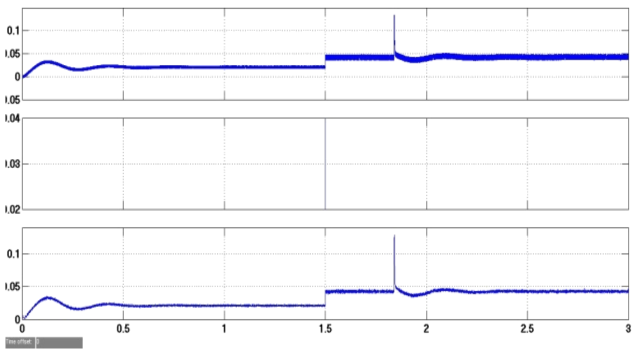

Fig. 9: Performance during sudden change in torque by using PI controller based BLDC motor

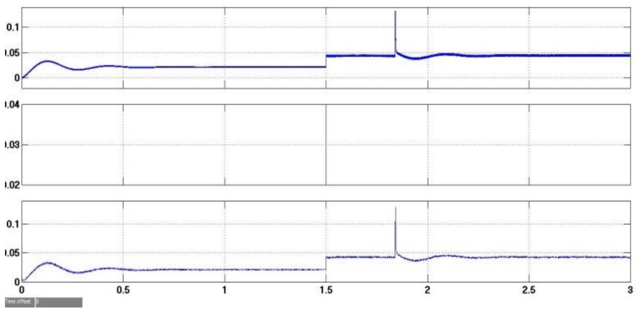

Fig. 10: Performance during sudden change in torque by using ANFIS controller based BLDC motor

C. Sudden Reference Speed Change:

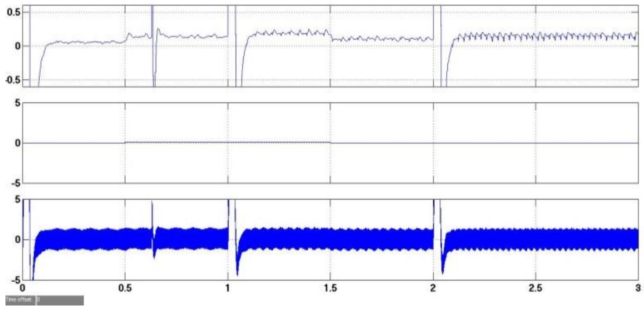

Fig. 11: Performance during sudden change in speed by using PI controller based BLDC motor

Fig. 12: Performance during sudden change in speed by using ANFIS controller based BLDC motor

VI. CONCLUSION

The brushless DC motor performance with ANFIS controller under different operating conditions is presented. The dynamic characteristics of the brushless DC motor such as speed, torque, current and voltages of the inverter components are observed and analyzed. It is observed that the performance of the drive is improved with ANFIS controller when compared to PI controller.This paper analyzes the main factors that influence the quickened torque performance for small inductance brushless dc motor. First, electromagnetic torque change is accomplished by decreasing current ripple in the compensation and conduction regions. Second, the influence torque is smothered by the aggravation torque controller.

A systematic approach of achieving the speed control of brushless dc motor by means of adaptive neuro fuzzy inference control system has been investigated in this paper. Simulink model was developed in Matlab with the ANFIS controller for the torque control of BLDCM. The control strategy was also developed by writing a set of 9 fuzzy rules according to the ANFIS control strategy with the back propagation algorithm in the back end. The main advantage of designing the ANFIS coordination scheme is to increse the performance of the BLDCM & to increase the dynamic Performance, Simulations were run in Matlab & the results were observed on the corresponding scopes. The outputs take less time to stabilize, which can be observed from the simulation results. Due to the incorporation of the ANFIS controller in loop with the plant, it was observed that the motor reaches the rated speed very quickly in a lesser time compared to the Mamdani method.

DC source	v	28
Rated accelerated torque	N.m	±0.05
Rated rotor speed	rad/s	±52.36
Back EMF cofficient	v.s/rad	0.08
Phase resistance	Ω	0.5
Phase inductance	µH	36
Buck converter PWM frequency	kHz	20
Three phase inverter PWM frequency	kHz	200

Table 2: BLDC Motor Control System Parameters

Comparison between PI controller and ANFIS controller used in torque of BLDC motor is as shown in table III

	PI Controller	ANFIS Controller
Inverter bus voltage	48V	44V
Quickend torque	0.001-0.012 N.m	0-0.04
Electromagnetic torque	0.03	0.025

Table 3: Comparison

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