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A Comparative Investigation on DTC of B4-Inverter-Fed BLDC Motor Drives Using Pi and Intelligent Controllers

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ABSTRACT- This paper gives a comparative investigation on Direct Torque Control of B4-Inverter-Fed Brush less DC Motor drive using PI and intelligent Controllers. The B4 inverter is just a reconfigured topology of ordinary six switched inverter. Direct torque control has some benefits such as faster torque response and reduced torque ripple for driving the brushless DC motors. The DTC of B4-inverter-fed BLDC motor drives are studied under four strategies, such as: 1) DTC-1: DTC of B4-inverter-fed BLDC motor drives using PI control; 2) DTC-2: DTC of B4-inverter-fed BLDC motor drives using FLC; 3) DTC-3: DTC of B4-inverter-fed BLDC motor drives using ANFIS; 4) DTC-4: DTC of B4-inverter-fed BLDC motor drives using ANN. A comparative study on the speed response and electromagnetic torque of the four DTC strategies are carried out. The simulation of all four DTC strategies is developed in MATLAB Simulink and from the simulation results, the comparisons are made.

KEYWORD- BLDC Motor, Direct Torque control, B4-inverter, PI, Fuzzy, ANN, ANFIS

I. INTRODUCTION AND LITERATURE REVIEW

Brushless dc motors are rapidly gaining popularity in automotive, aerospace, medical and industrial automation industries. As a result of the absence of mechanical commutators and brushes and the permanent magnet rotor, brushless dc motors have many advantages over the brush dc and induction motor. The advantages of brushless dc motors such as long operating life and high reliability, low audible noise operation, high efficiency, high dynamic response [1].

Among the control strategies that exhibit a high torque dynamic, one can distinguish the direct torque control (DTC). DTC strategies have been widely implemented in squirrel cage induction machine drives. They allow a direct control of the electromagnetic torque and the stator flux through the application of suitable combinations of the control signals of the inverter switches [2]. And then researches were made on DTC using conventional converters such as six switch inverters (B6- inverters) [3]-[7] and also in unconventional converters [8]-[10]. Low-Cost Direct Torque Control Algorithm for Induction Motor without AC Phase Current Sensors was proposed [5]. Researches were made to reduce the switching losses, lower harmonic distortion of the motor phase currents and a higher capability to operate at low levels of the dc-bus voltage, which could be of interest for electric vehicle (EV) and hybrid electric vehicle (HEV) applications [7].

Among the unconventional topologies, one can distinguish the B4-inverter which results from the reconfiguration of the B6-inverter in the case of a switch/leg failure. Such a reconfiguration is a vital requirement in some applications, especially electric and hybrid propulsion systems, in so far as the vehicle reliability is concerned. It is shown that it is possible for an FSTP (four-switch three-phase) inverter to provide similar performance to an SSTP (six-switch three-phase) inverter when driving a PM BLAC machine [9]. Operation of the same machine at the same operating point in the torque-speed plane by feeding from both a B6 and a B4 circuit with PWM, two-level current control, and PAPWM were made by Heinz w. Van der broeck and Jacobus d. van wyk [11].

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Torque-ripple control of the brushless dc motor has been the main issue of the servo drive systems in which the speed fluctuation, vibration, and acoustic noise should be minimized. In order to minimize the torque ripple a hysteresis current controller based control is proposed by Sung Jun Park, HanWoong Park, Man Hyung Lee, and Fumio Harashima [12]. Different DTC strategies have been successfully implemented in B6-inverter-fed BLDC motor drives [13]-[16]. Torque ripple reduction in BLDC motor with non-ideal back emf was proposed by Jiancheng Fang, Haitao Li, and Bangcheng Han. In this method a novel automatic control method of torque is proposed. With this method, the current control rule is designed, and the duty cycle of pulse width modulation (PWM) is regulated in real time by measuring the wave function of back EMF [15].

Concerning the DTC of BLDC drives fed by the reduced structure inverters, the most recent and high-performance strategy reported in the literature has been developed by Ozturk et al. [17]. It deals with the DTC of BLDC motors with a B4-inverter in the armature. The proposed DTC strategy considers a vector selection suitable that enables the independent control of the electromagnetic torques developed by the phases connected to the inverter legs during their simultaneous conduction. Intelligent control techniques are introduced into DTC to improve the performance of the system [18]. Conventional DTC has also some disadvantages such as possible problems during starting, low speed operation, high requirements upon flux and torque estimation and variable switching frequency. These are disadvantages that we want to remove by using and implementing modern resources of artificial intelligence[19].Direct torque control of brushless dc motor drives with reduced starting current using fuzzy logic controller has been successfully implemented by N. Parhizkar, M. Shafiei, and M. Bahrami Kouhshahi in a B6 inverter [20].

II. VARIABLE FREQUENCY DRIVE CONTROL

A Variable Frequency Drive (VFD) is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Other names for a VFD are variable speed drive, adjustable speed drive, adjustable frequency drive, AC drive, micro drive and inverter. Frequency (or hertz) is directly related to the motor’s speed (RPMs). In other words, the faster the frequency, the faster the RPMs go. If an application does not require an electric motor to run at full speed, the VFD can be used to ramp down the frequency and voltage to meet the requirements of the electric motor’s load. As the application’s motor speed requirements change, the VFD can simply turn up or down the motor speed to meet the speed requirement.

a. DIRECT TORQUE CONTROL

Direct torque control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor. The general block diagram of Direct Torque Control (DTC) is shown in Figure 1.

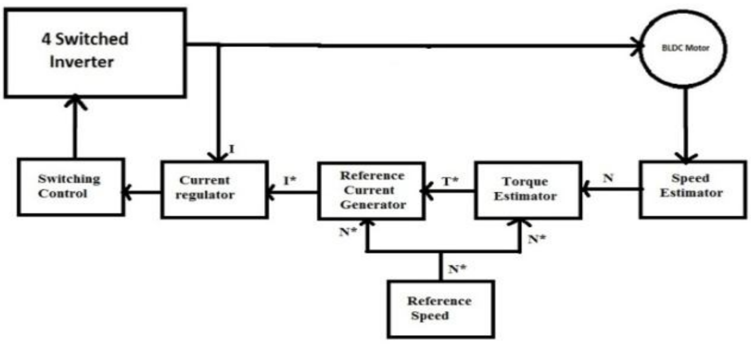

FIGURE-1 OVERALL BLOCK DIAGRAM OF DTC OF B4-INVERTER-FED BLDC MOTOR DRIVE

In a BLDC motor, the coil is wound on the stator, the rotor has surface-mounted permanent magnets, and the brush commutator is replaced with the electronic commutator. BLDC motors come in single-phase, 2-phase and 3-phase configurations. The phase currents and corresponding back EMFs are shown in figure-2

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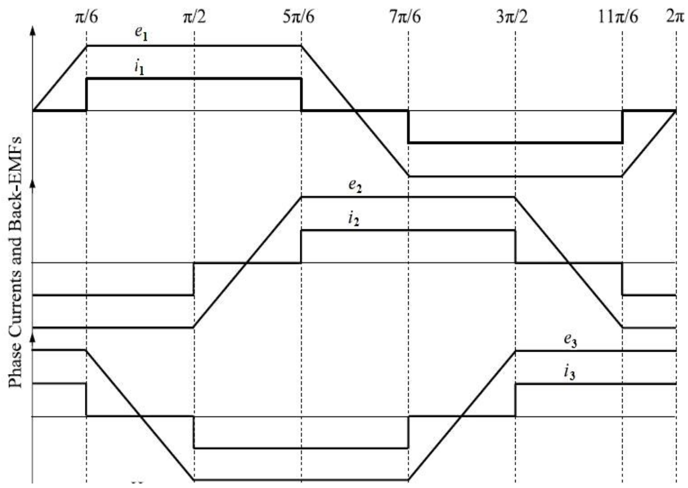

FIGURE-2 BLDC MOTOR PHASE CURRENTS AND BACK EMFS

b. VOLTAGE AND TORQUE EQUATIONS OF BLDC MOTOR

The voltage and torque equations of brushless dc motors are given by equations 1, 2, 3 & 4.

$$V_1 = RI_1 + L\frac{di_1}{dt} + e_1 \qquad \textbf{(1)}$$

$$V_2 = RI_2 + L\frac{di_1}{dt} + e_2 \qquad \textbf{(2)}$$

$$V_3 = RI_3 + L\frac{di_1}{dt} + e_3 \qquad \textbf{(3)}$$

$$T_e = K_f w_m + j\frac{dw_m}{dt} + T_l \qquad \textbf{(4)}$$

Where,

V_1, V_2, V_3 - phase voltages of 1, 2, 3
I_1, I_2, I_3 - phase currents of 1, 2, 3
e_1, e_2, e_3 - back emf of phase 1, 2, 3
T_e, T_l - Electrical torque and load torque
ω_m - Rotor speed
j - Rotor inertia
K_f - Friction constant
R, L - resistance and inductance of each phase

c. OPERATION OF B4 INVERTER

In a B4 inverter the output voltage is controlled by means of only four switches. The phase-3 voltage is made zero by turning ON single switch in the adjacent arms simultaneously [21].

Let **V1, V2, V3,** and **V4 be** the four active voltage vectors generated by the B4-inverter under the two-phase conduction mode. The corresponding switching combinations ($S1$ $S2$ $S3$ $S4$) are equal to (1000), (0010), (0100), and (0001), respectively, where, from left to right, the binary values denote the state of the upper and lower switching signals, corresponding to phase- and phase-2, respectively. These combinations yield four operating sequences characterized by the conduction of phase-3

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Table-1 B4-Inverter Switching

Switch ON	Phase-1	Phase-2	Phase-3
S1	+Vdc	0	-Vdc
S2	-Vdc	0	+Vdc
S3	0	+Vdc	-Vdc
S4	0	-Vdc	+Vdc

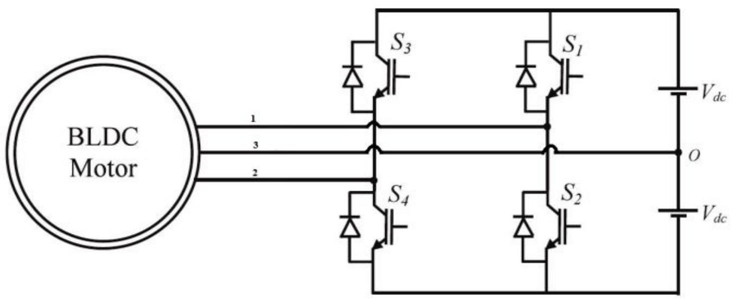

FIGURE-3 CIRCUIT DIAGRAM OF B4-INVERTER FED BLDC MOTOR DRIVE

d. HYSTERESIS BAND CURRENT CONTROL PWM

The hysteresis band current control PWM has been used because of its simple implementation, fast transient response. In these methods of current control, the load currents are measured and compared with the reference currents. The error is used as the input to the PWM which is used to drive the switching frequency of inverter.

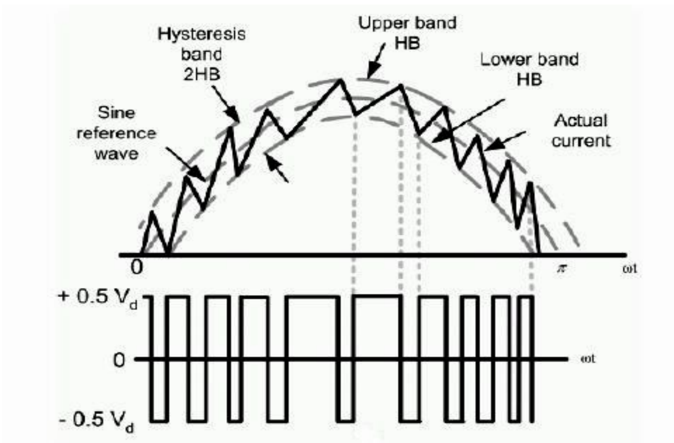

FIGURE-4 HYSTERESIS CURRENT CONTROLLER BASIC STRUCTURE

e. INTELLIGENT CONTROL

Intelligent control describes the discipline where control methods are developed that attempt to emulate important characteristics of human intelligence. These characteristics include adaptation and learning, planning under large uncertainty and coping with large amounts of data.

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III. DESIGN OF SPEED CONTROLLER BASED ON FUZZY

The FLC is designed using MATLAB – FIS Editor. The linguistic variables chosen for this controller are Error, CE and output. In this, the error and CE are the input linguistic variables and output is the output linguistic variable. Each of the input and output fuzzy variables is assigned seven linguistic fuzzy subsets varying from Negative Big (NB) to Positive Big (PB). Each subset is associated with a triangular membership function to form a set of seven membership functions for each fuzzy variable.

The linguistic terms chosen for this controller are five.

- Negative Big (NB)
- Negative Small (NS)
- Zero (ZE)
- Positive Small (PS)
- Positive Big (PB)

After assigning the input, output ranges to define fuzzy sets, mapping each of the possible seven input fuzzy values of speed deviation, active power deviation to the seven output fuzzy values is done through a rule base. Thus the Fuzzy Associative Memory (FAM) comes into picture (Figure-).

Error	CE				
	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

The developed Fuzzy logic controller in FIS editor is shown in figure-5

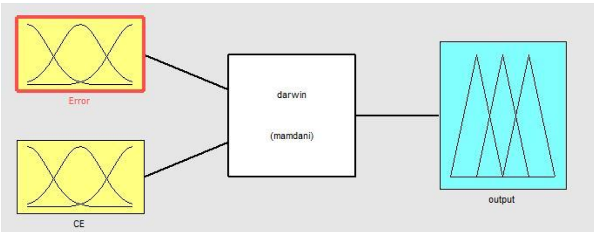


Figure-5 FIS editor for DTC of BLDC Motor

IV. DESIGN OF SPEED CONTROLLER BASED ON ARTIFICIAL NEURAL NETWORK

Neural network consists of simple elements similar to biological nervous systems. These networks can be trained by adjusting the value of connections and weights between the elements to perform a specific function. The training is done based on comparison of output and target until the output matches the target. The neural network is developed using MATLAB-Neural Network Fitting toolbox.

The Artificial neural network developed is a two-layer feed-forward network with sigmoid hidden neurons and linear output neurons (fit net), can fit multi-dimensional mapping problems arbitrarily well, given consistent data and 10 neurons in its hidden layer. (Fig-)

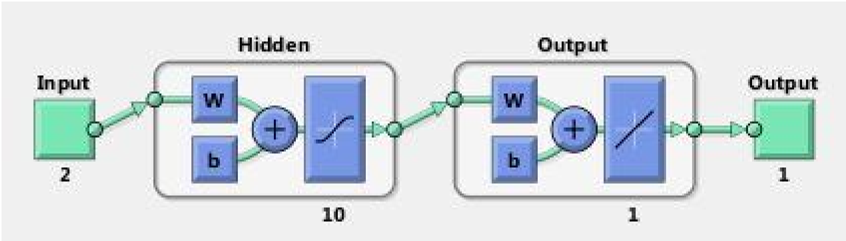


Figure-6 Neural Network Architecture for DTC of BLDC Motor

The network is trained with Levenberg-Marquardt back-propagation algorithm. The network is trained with the data's obtained from the inputs and outputs of the fuzzy logic controller. The CE, Error, output values are send to workspace and stored in a table. Using these data's the network is trained.

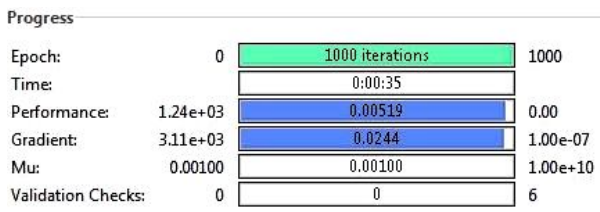


Figure-7 ANN training for DTC of BLDC Motor

V. DESIGN OF ANFIS BASED SPEED CONTROLLER

The Adaptive Neuro-Fuzzy Inference System is developed using Matlab ANFIS editor. The input to the ANFIS controller is speed error and cumulative error (CE). The output is torque command. The error, CE and output of the FLC is send to the workspace and the data's are stored in a array. The ANFIS controller is trained using the data's from the workspace. The controller is trained repeatedly till the error reaches a minimum value.

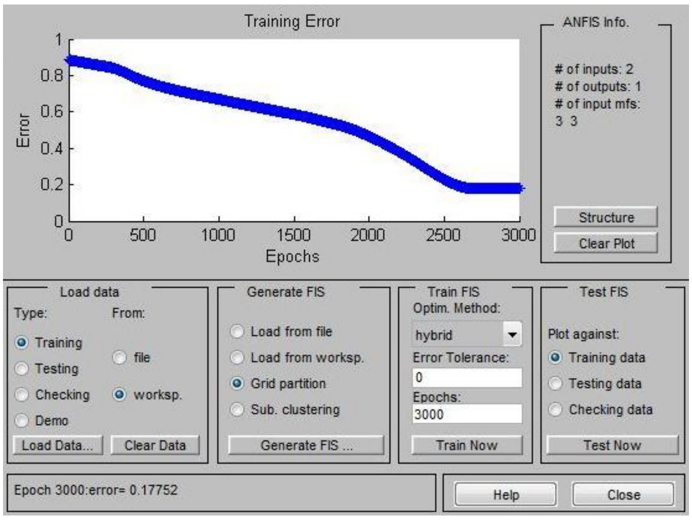
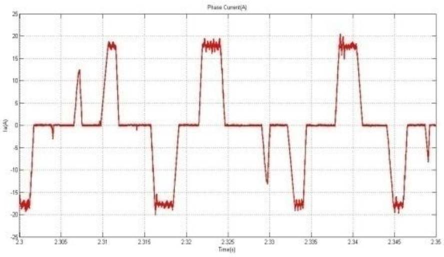


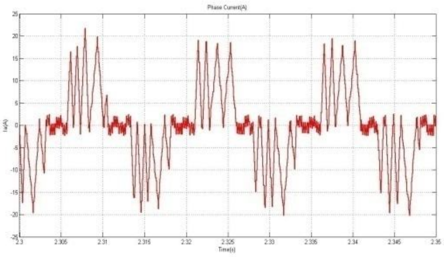
Figure-8 ANFIS editor for DTC of BLDC Motor

VI. SIMULATION RESULTS

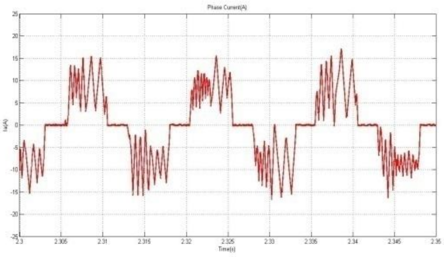
The simulation results of Direct Torque Control of B4 Inverter fed BLDC Motor drive is presented.The waveforms are obtained for the following conditions, initially at t = 0 the speed is set to 1200rpm and load of 1 N-m is applied and when the time reaches 1.5s a loads of 5 N-m is applied and when the time reaches 2s the speed is set to1000rpm. The simulation is made for 3seconds.



9(A)



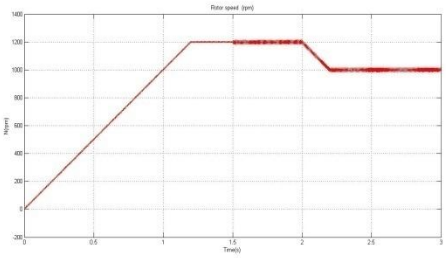
9(B)



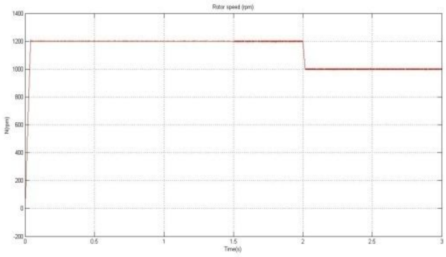
9(C)

9(D)

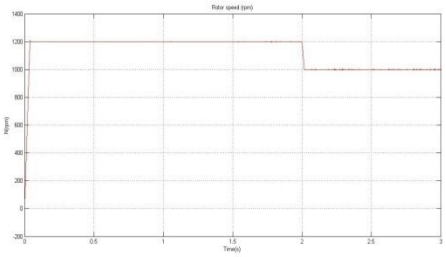
FIGURE 9 STEADY-STATE ELECTRICAL FEATURES OF THE B4-INVERTER-FED BLDC MOTOR DRIVE: 9(A) STATOR CURRENTS USING PI CONTROLLER 9(B) STATOR CURRENT USING FLC 9(C)STATOR CURRENT USING ANN 9(D)STATOR CURRENT USING ANFIS



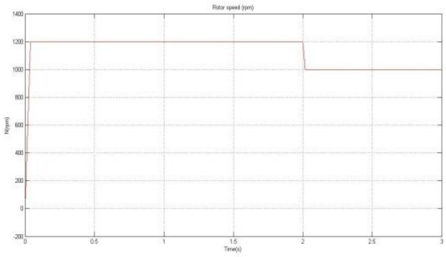
10(A)



10(B)



10(C)



10(D)

FIGURE 10 STEADY-STATE MECHANICAL FEATURES OF THE B4-INVERTER-FED BLDC MOTOR DRIVE: 10(A) SPEED RESPONSE OF BLDC MOTOR USING PI BASED CONTROL 10(B) SPEED RESPONSE OF BLDC MOTOR USING FLC 10(C) SPEED RESPONSE OF BLDC MOTOR USING ANN 10(D) SPEED RESPONSE OF BLDC MOTOR USING ANFIS

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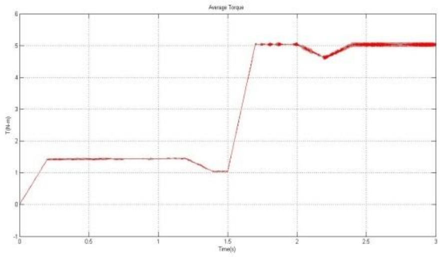
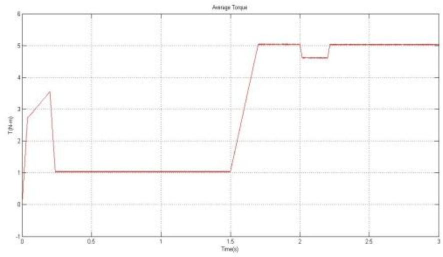
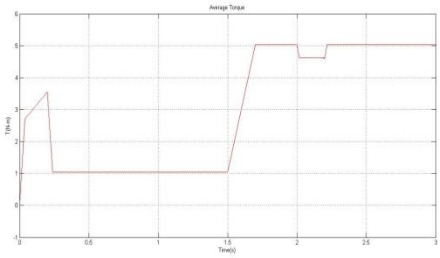


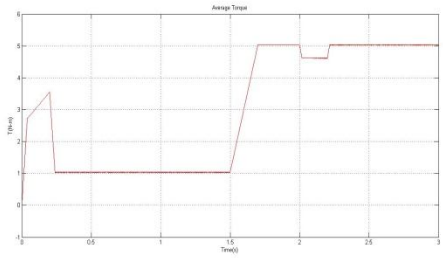
11(A)



11(B)

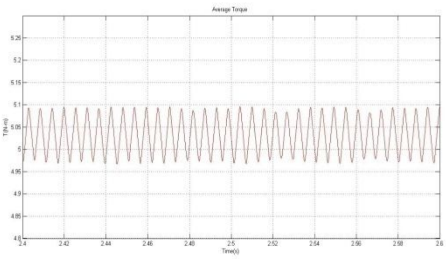


11(C)

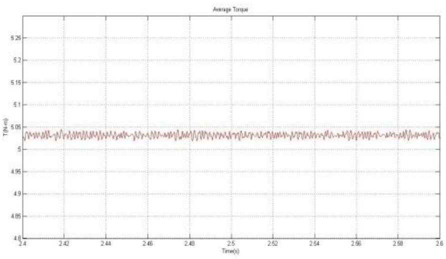


11(D)

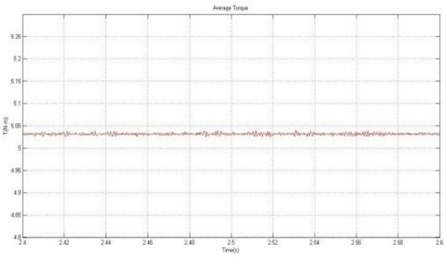
FIGURE 11 ELECTROMAGNETIC FEATURES OF THE B4-INVERTER-FED BLDC MOTOR DRIVE: 11(A) ELECTROMAGNETIC TORQUE USING PI BASED CONTROL 11(B) ELECTROMAGNETIC TORQUE USING FLC 11(C) ELECTROMAGNETIC TORQUE USING ANN 11(D) ELECTROMAGNETIC TORQUE USING ANFIS



12(A)



12(B)



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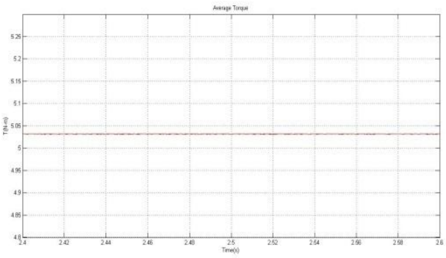

12(D)

FIGURE 12 STEADY-STATE ELECTROMAGNETIC TORQUE: 12(A) PI BASED ELECTROMAGNETIC TORQUE ZOOMED 12(B) FLC BASED ELECTROMAGNETIC TORQUE ZOOMED 12(C) ANN BASED ELECTROMAGNETIC TORQUE ZOOMED 12(D) ANFIS BASED ELECTROMAGNETIC TORQUE ZOOMED

VII. CONCLUSION

Direct Torque Control of B4 Inverter fed BLDC Motor drives using PI and Intelligent Controller is demonstrated. When coming to the converter side only four switches are used instead of six switches which reduce the cost of the converter. Simulations are made using PI, FLC, ANN, and ANFIS. The speed and torque response using PI and

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intelligent control are studied. From the output waveforms it is seen that the performance of the system using ANFIS is much better when compared to other control techniques. The speed response of intelligent controllers based DTC is 30 times faster than PI based DTC. In addition by using ANFIS, the torque ripples are reduced to minimum.

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