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By C. Subba Rami Reddy & M. Surya Kalavathi

KSRM College of Engineering, India

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Keywords: *BLDC motor, switching function, FLC, ANFIS controller, performance specifications.*

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PERFORMANCEANALYSISOFBLDCMOTORDRIVEUSINGNEWSIMULATIONMODELWITHFUZZYANDANFISSPEEDCONTROLLERS

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C. Subba Rami Reddy [α] & M. Surya Kalavathi [σ]

Abstract- This paper presents the mathematical model of the brushless DC (BLDC) motor drive fed by the hysteresis current controlled inverter, which is designed using the new switching function concept. The developed simulation model is applied with the fuzzy logic controller (FLC) and adaptive neuro fuzzy inference system (ANFIS) controller as speed controllers to enhance the performance of the BLDC motor drive system. The complementary strengths of FLC and neural networks are combined together to obtain the ANFIS controller. The ANFIS controller is trained by the data of closed loop BLDC motor drive system simulated with PI controller. The ANFIS controller avoids the selection of fuzzy control rules and tuning of membership functions in the manual manner as done in FLC. A comparative study of different performance specifications is proposed between FLC and ANFIS speed controller as applied to the BLDC motor drive system. The simulation results show that the ANFIS controller is more effective as compared to FLC during most of the operating conditions considered.

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I. Introduction

Now a days, the brushless dc (BLDC) motors are very widely used in many applications because of high efficiency, high power density, silent operation, long operating life, low maintenance and good dynamic performance [1-5]. Lot of research work is progressing towards the BLDC motor drive due to the increased demand of such systems in the market [6-9]. However, the use of BLDC motors is restricted due to the complexity involvement in the speed control for applications with the variable speed and varying loads [10-13]. The classical controllers with fixed gains may not work properly due to the changes in plant dynamics with ageing process, parameter variations and external disturbances [14-16].

Fuzzy control is one of the most interesting techniques that can be well applied for the control of imprecise, nonlinear and ill-defined systems [17-21]. The selection of membership functions and the development of fuzzy control rules is a difficult task without the information from the skilled operator. More over the fuzzy control rules could not be defined properly if the skilled operator is unable to give the exact instructions about the process operation. The artificial neural networks have the learning capability which gains the knowledge of a process automatically from the sample input and output relationship of the process [22-23]. This paper introduces the implementation fuzzy logic controller (FLC) and adaptive neuro fuzzy inference system (ANFIS) controller for the speed control of BLDC motor drive system to improve the performance at different operating conditions. This paper is organized in the following manner. Section II illustrates the description of BLDC motor drive that consists of speed controller, current controller, BLDC motor and inverter. Section III presents the simulation results of the drive with FLC as speed controller. Section IV explains the application of ANFIS speed controller to the BLDC motor drive system along with the simulation results. Section V gives the comparative performance of BLDC motor drive for different operating conditions between FLC and ANFIS controller. Finally the main concluding remarks are given in section VI.

II. Description of BLDC Motor Drive System

The block diagram of BLDC motor drive system with the combination of FLC and the neural network as speed controller is shown in figure 1. The drive system consists of BLDC motor, rotor position sensor, combined FLC and neural network known as ANFIS controller and three phase voltage source inverter.

There are two basic control loops in the description of the drive system known as speed control loop and current control loop [24-25]. The speed control loop is the outer control loop which consists of BLDC motor, rotor position sensor, speed controller, reference current generator, hysteresis controller and three phase voltage source inverter. The current control loop is the inner control loop which consists of reference current generator, hysteresis current controller and three phase voltage source inverter. The back electro motive force (EMF) wave forms of BLDC motor are in trapezoidal shape. These trapezoidal waveforms for all the three phases are built based on the rotor position (θ).

Author α: Associate professor, Electrical and Electronics Engineering, KSRM College of Engineering, Kadapa, Andhra Pradesh, India. e-mail: csubbaramireddy2020@gmail.com
Author σ: Professor, Electrical and Electronics Engineering, JNTUH, Hyderabad, Andhra Pradesh, India. e-mail: munagala12@yahoo.co.in

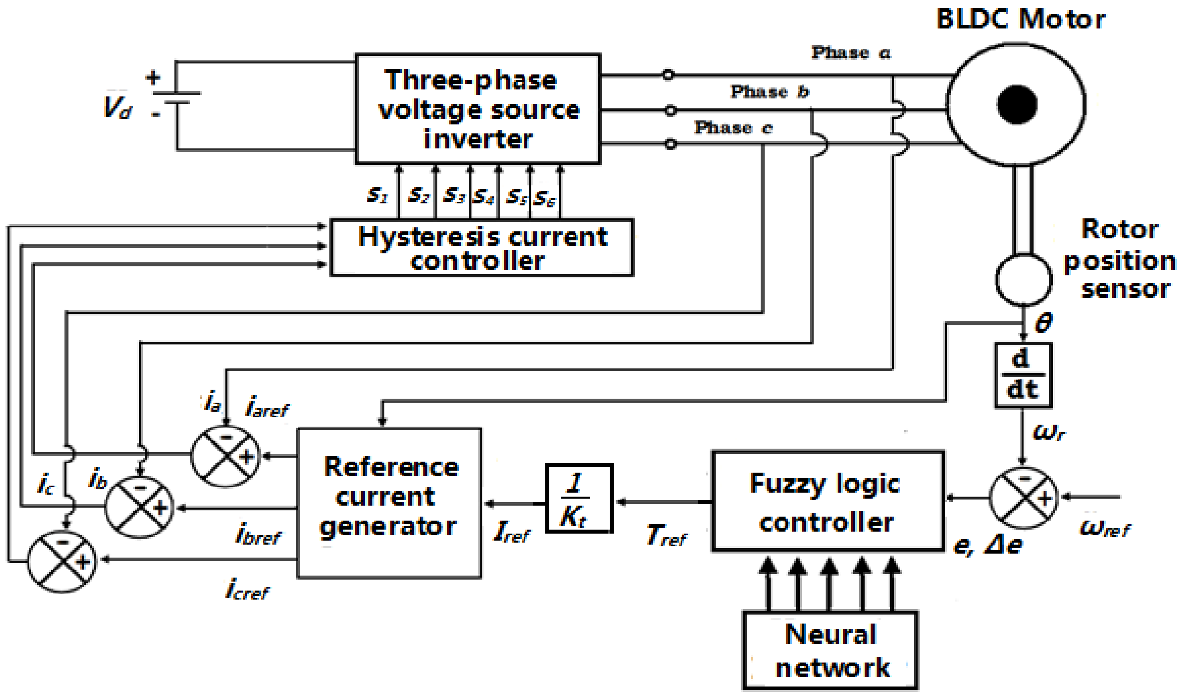

Fig. 1 : Block diagram of BLDC motor drive with the combined FLC and neural network based speed controller

The rotating speed (ω_r) of BLDC motor is determined by means of knowing the position of the rotor from the back EMF wave forms. The actual speed of the motor is compared with the reference speed (ω_{ref}) and then the error signal (e) is given to the speed controller. The two types of speed controllers considered are FLC and ANFIS controller. The speed controller processes the error signal of speed to generate the signal equivalent to the reference torque (T_{ref}).

The reference torque divided by the torque constant (K_t) gives the reference current (I_{ref}). The reference current generator generates the reference currents i_{aref}, i_{bref} and i_{cref} for phases a, b and c based on the rotor position. The reference phase currents are compared with the actual phase currents to generate the current error in the respective phases. The hysteresis current controller generates the firing pulses for the semiconductor switches of the three phase inverter based on the values of current error and the rotor position.

The three phase inverter fed by the constant DC supply produces the variable voltage and frequency based on the turn-on and turn-off of semiconductor switches. Therefore the inner loop synchronizes the currents while the outer loop synchronizes the speed. The overall simulation model of the drive system shown in figure 2 is developed using MATLAB and Simulink environment by considering the basic process equations of each component of the drive system. The attention is made to focus the implementation of FLC and ANFIS controller as speed controllers rather than the details of modeling of BLDC motor drive system.

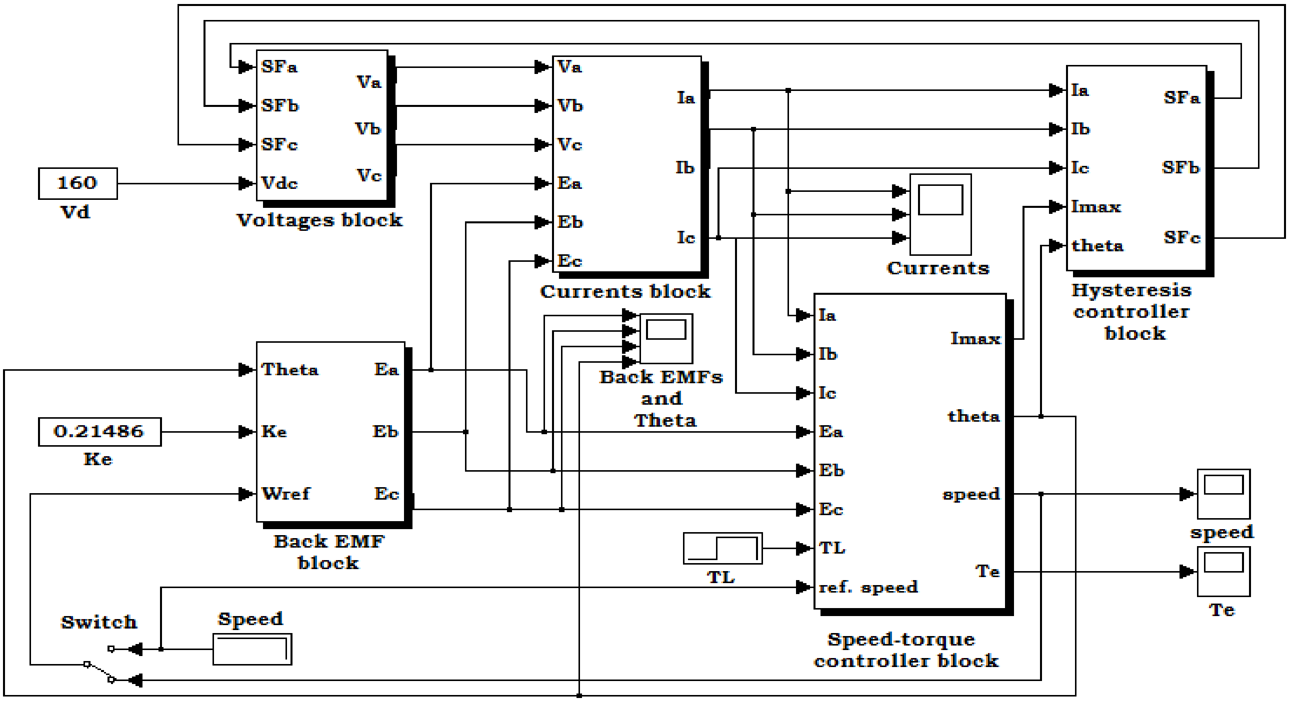

Figure 2 : Simulation model of drive system using MATLAB and Simulink

III. Implementation of BLDC Motor Drive with FLC

The inputs of FLC are signals of error (e) and change in error (Δe) in the speed of BLDC motor from the reference value. The seven membership functions are chosen for the representation of inputs and the output of FLC. They are large negative (LN), medium negative (MN), small negative (SN), zero (ZE), small positive (SP), medium positive (MP) and large positive (LP). The triangular membership functions are chosen for the membership functions of MN, SN, ZE, SP and MP while the trapezoidal membership functions are chosen for the membership functions of LN and LP. The ranges of input and output membership functions of FLC over the universe of discourse are shown in figures 3 and 4. The output control signal (u_f) of FLC is as per the fuzzy control rules stored in the rule base shown in table 1.

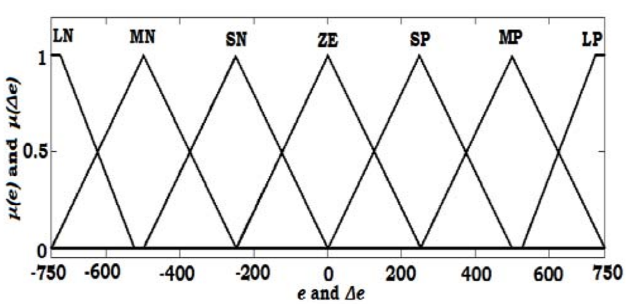

Figure 3 : Membership functions for the inputs of error and change in error

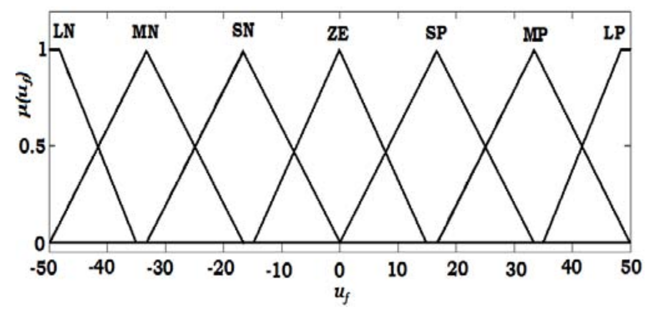

Figure 4 : Membership functions for the output of FLC

Table 1 : Fuzzy rules for the control signal (u_f) .

e/Δe	LN	MN	SN	ZE	SP	MP	LP
LN	LN	LN	LN	MN	SN	SN	ZE
MN	LN	MN	MN	MN	SN	ZE	SP
SN	LN	MN	SN	SN	ZE	SP	MP
ZE	LN	MN	SN	ZE	SP	MP	LP
SP	MN	SN	ZE	SP	SP	MP	LP
MP	SN	ZE	SP	MP	MP	MP	LP
LP	ZE	SP	SP	MP	LP	LP	LP

a) *Simulation Results of Drive with FLC*

The simulation results of BLDC drive with FLC are shown in figures 5 to 10 for various operating conditions at a set speed of 3500 rpm. The parameters of the BLDC motor considered are 4 poles, 1 HP, star connected, 3500 rpm, 160 V DC supply, 5 A, resistance of 0.75Ω per phase, self inductance minus mutual inductance of 0.00305 H per phase, torque constant of 0.21476 N-m/A, moment of inertia of 0.82614 e-4 Kg-m2 and back EMF constant of 0.10743 V-s per radian. The sudden load of 0.662 N-m is applied at 0.05 second and withdrawn at 0.12 second. The motor speed is changed at 0.15 second to a value equal to the set speed but in the opposite direction.

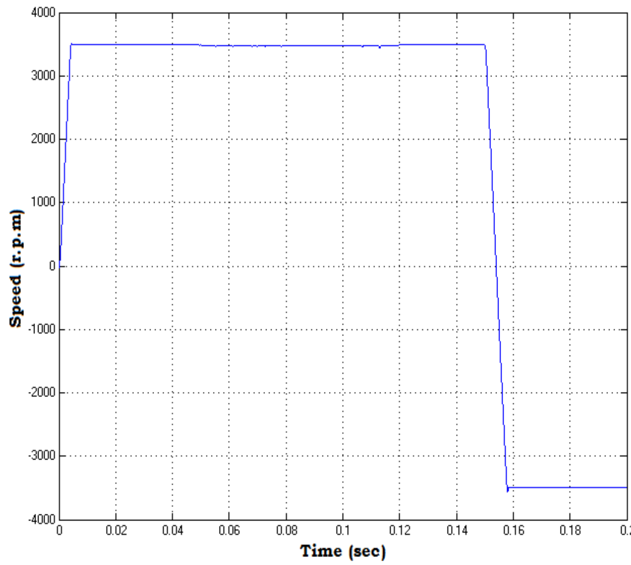

Figure 5 : Speed response of drive with FLC

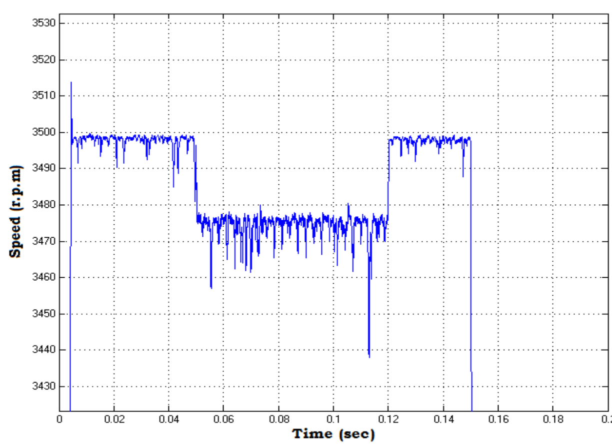

Figure 6 : Magnified view of speed response with FLC

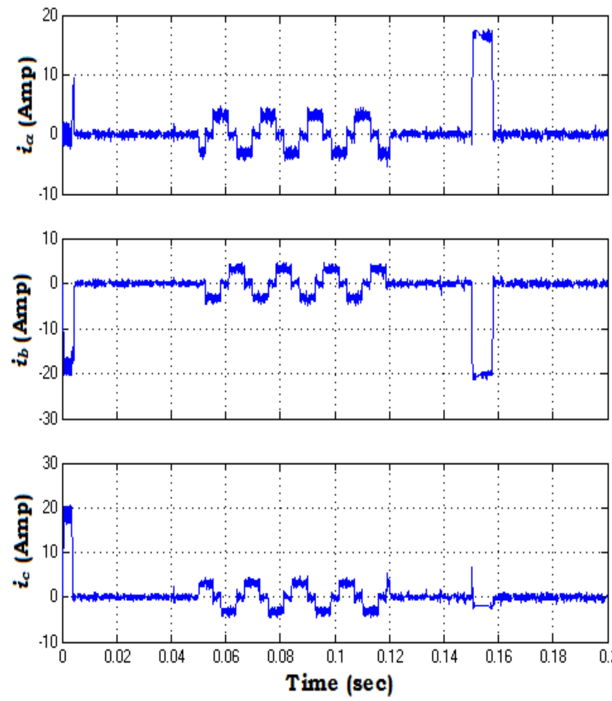

Figure 7 : Phase current waveforms with FLC

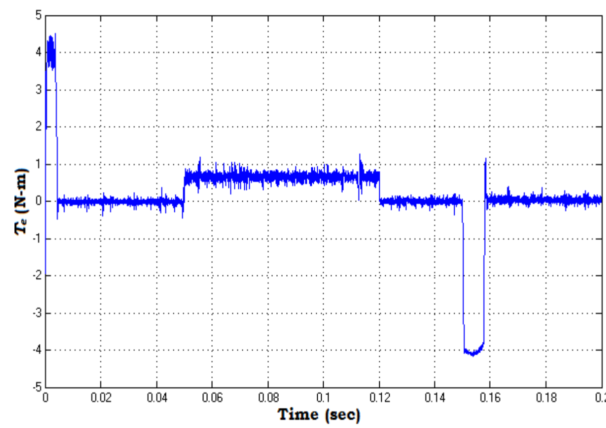

Figure 8 : Torque response of drive with FLC

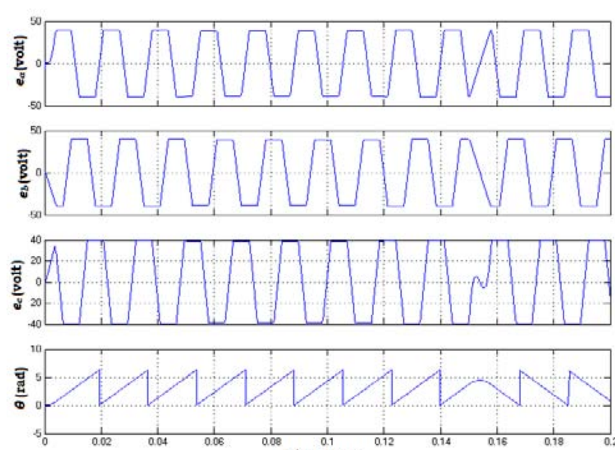

Figure 9 : Back EMFs and rotor position with FLC

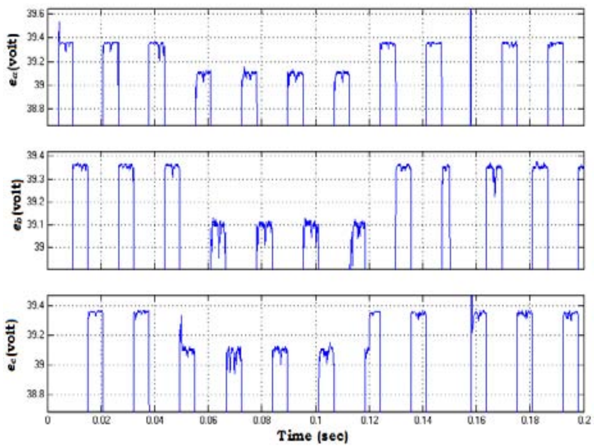

Figure 10 : Magnified view of back EMFs with FLC

IV. Implementation of BLDC Motor Drive with ANFIS Controller

The properties of both fuzzy control and artificial neural networks are combined to produce the ANFIS controller. The FLC is provided with the learning capability by the structure of neural network that helps the FLC to select the best possible ranges for the input and output membership functions that match the sample input and output data. The response of BLDC motor drive with the proportional-integral (PI) controller is used as sample input and output data to train FLC. The basic structure of ANFIS network obtained through the MATLAB is shown in figure 11. The trained membership functions with the best possible ranges for error (e) and change in error (Δe) are shown in figure 12.

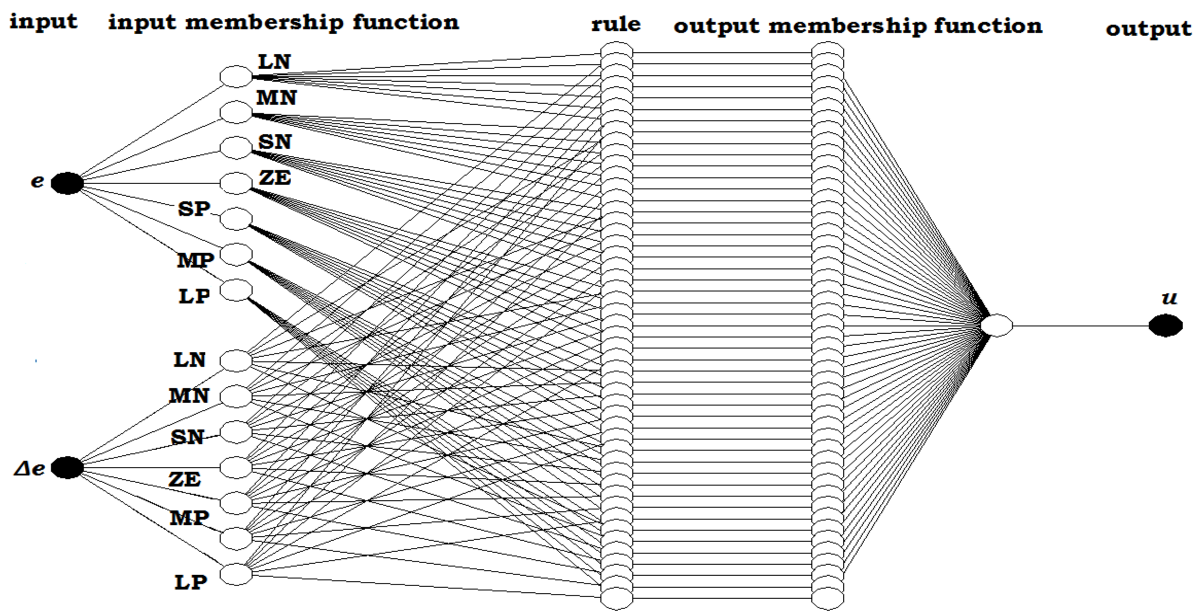

Figure 11 : The network of ANFIS controller

The chosen fuzzy inference system for FLC is Takagi-Sugeno-Kang type of fuzzy inference system. The selected membership functions are the generalized bell shaped one. The parameters of membership functions are tuned by both the back propagation and least squares method through the neural networks structure. The structure of neural network is helping in tuning and selection process of membership functions and fuzzy control rules respectively thereby eliminating the use of human expert. The updating of parameters through the learning process is facilitated by the gradient vector.

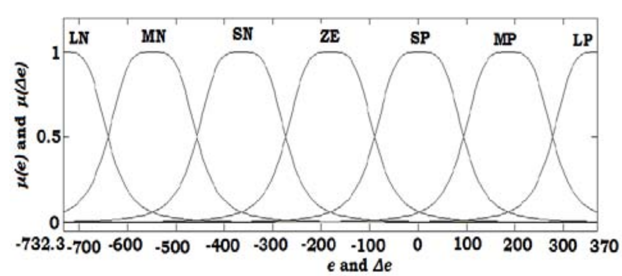

Figure 12 : Membership functions for error and change in error

a) Simulation Results of Drive with ANFIS Controller

The simulation results of BLDC drive with ANFIS controller are shown in figures 13 to 18 for different operating conditions as done with FLC at a set speed of 3500 rpm.

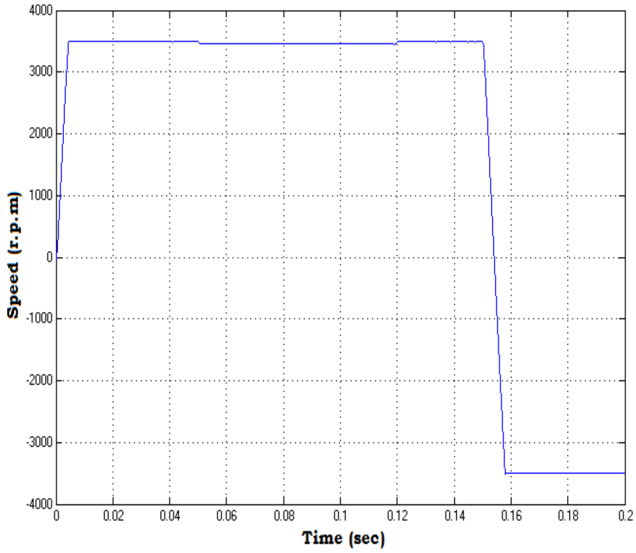

Fig. 13 : Speed response of drive with ANFIS controller

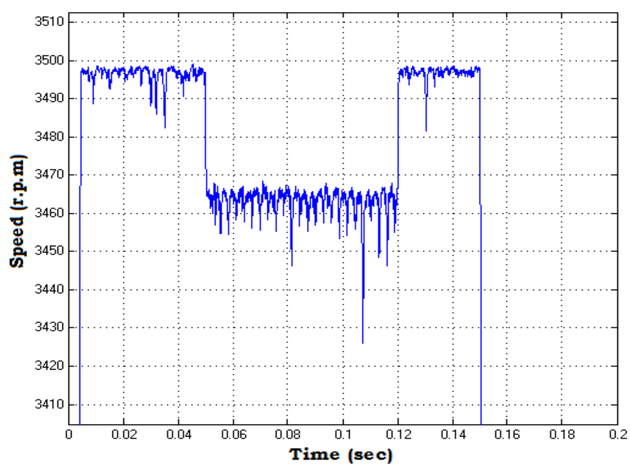

Fig. 14 : Magnified view of speed response with ANFIS controller

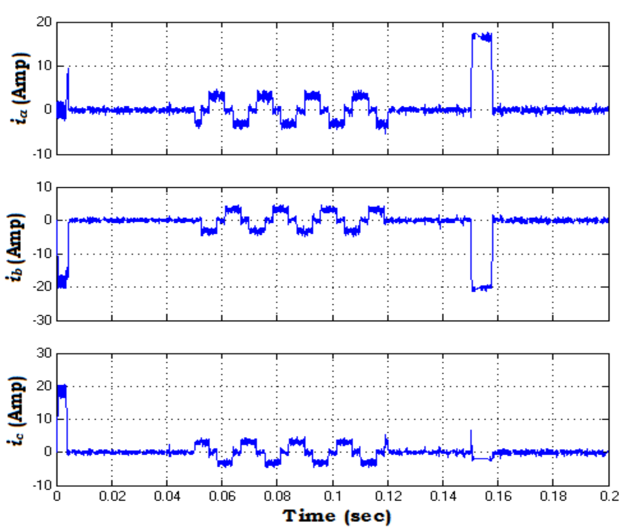

Fig. 15 : Phase current waveforms with ANFIS controller

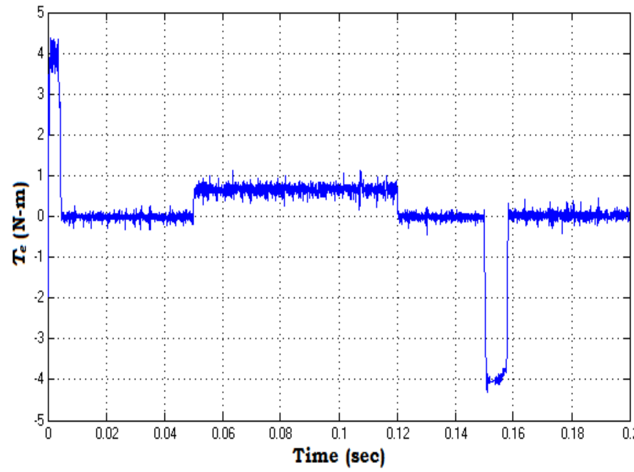

Fig. 16 : Torque response of drive with ANFIS controller

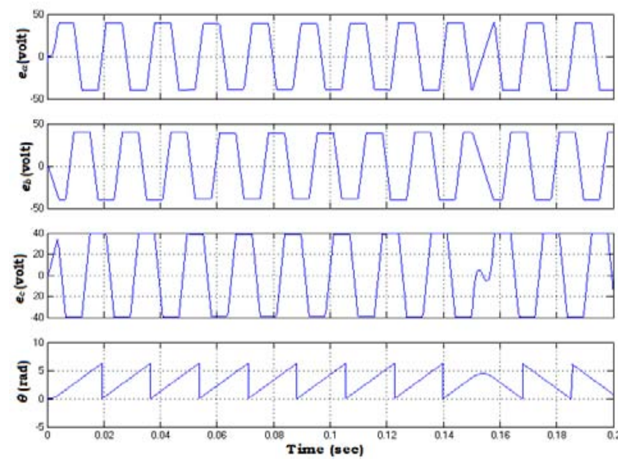

Fig. 17 : Back EMFs and rotor position with ANFIS controller

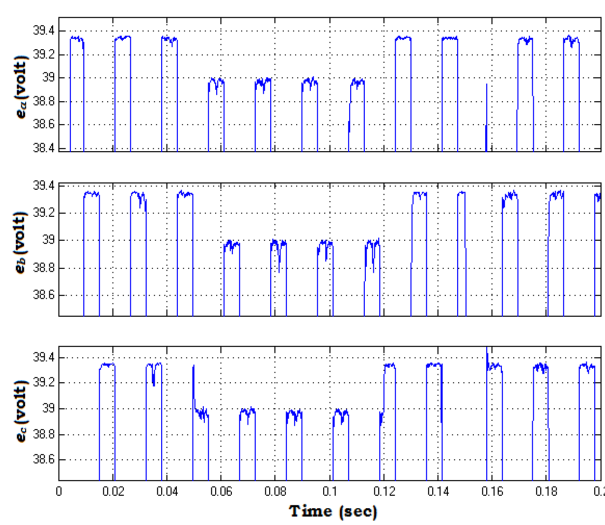

Fig. 18 : Magnified view of back EMFs with ANFIS controller

Global Journal of Researches in Engineering (F) Volume XIV Issue IV Version I Year 2014

V. Comparison of Performance Indices between FLC and ANFIS Controller

A comparison of FLC and ANFIS controller is carried out in terms of different performance indices at various set speeds for different operating conditions. The table 2 shows the comparison for the performance specifications of settling time, steady state error, peak overshoot and time taken to reach the set speed in the reverse direction between FLC and ANFIS controller. The table 2 shows the comparison for the error constants of integral of absolute error (IAE), integral of squared error (ISE), integral of time weighted absolute error (ITAE) and integral of time weighted squared error (ITSE) between FLC and ANFIS controller.

Table 2 : Comparison of performance specifications

Reference speed in rpm	Type of Controller	settling time in sec	Steady state error in rpm	Dip in speed at a load of 0.662 N-m in rpm	Peak Overshoot in rpm	Settling time during speed reversal in sec
3500	FLC	0.0048	9	35	13.8	0.0092
	ANFIS	0.00461	11	40	1	0.0095
3100	FLC	0.0049	3	30	49.33	0.0085
	ANFIS	0.0046	3	40	55.1	0.0082
2600	FLC	0.00455	2	30	88.65	0.0069
	ANFIS	0.0042	0.9	40	22.39	0.0067
2100	FLC	0.0044	0.6	30	127.4	0.0062
	ANFIS	0.0044	0.4	40	72.3	0.006
1600	FLC	0.004	0.4	30	149	0.0049
	ANFIS	0.00353	0.4	37	74.44	0.0049
1100	FLC	0.003	0.4	24	116.7	0.004
	ANFIS	0.0028	0.4	35	38.18	0.0038

Table 3 : Comparison of error constants

Reference speed in rpm	Type of Controller	IAE	ISE	ITAE	ITSE
3500	FLC	0.8379	219.3	0.001193	0.2356
	ANFIS	0.8425	220	0.001209	0.2379
3100	FLC	0.6617	155.1	0.0008305	0.1489
	ANFIS	0.6703	157.3	0.0008512	0.1528
2600	FLC	0.4795	96.1	0.0005099	0.07939
	ANFIS	0.4808	95.93	0.0005148	0.0796
2100	FLC	0.3398	56.69	0.0003074	0.04047
	ANFIS	0.333	54.72	0.0002998	0.03832
1600	FLC	0.1991	26.27	0.0001324	0.01498
	ANFIS	0.2011	26.01	0.0001371	0.01487
1100	FLC	0.1016	9.634	$4.645X10^{-5}$	0.00425
	ANFIS	0.1072	9.932	$5.416X10^{-5}$	0.00439

a) Starting Performance

The time taken by the BLDC motor to settle at the set speed from standstill is observed for FLC and ANFIS controller at different set speeds of 3500, 3100, 2600, 2100, 1600 and 1100 rpm. It is found that the drive is taking less time with ANFIS controller for all the speeds. ANFIS controller is giving less overshoot at all speeds except at 3100 rpm as compared to FLC. The steady state error is almost equal in both the cases.

b) Speed Reversal and Load Perturbation

The drive rotating at set speed is suddenly reversed to rotate in the opposite direction. The ANFIS controller is attaining the set speed in the reverse direction quickly at most of the speeds. When the drive is running under steady state condition, a rated load of 0.662 N-m is applied at time of 0.05 second and withdrawn at 0.12 second. The dip in the speed is slightly high with ANFIS controller as compared to FLC.

VI. Conclusion

The simulation model of BLDC motor drive is developed to study the transient and steady state performance with FLC and ANFIS controller. The use of expert in selection of fuzzy control rules and tuning the membership functions is eliminated. The ANFIS controller is giving better performance during the different operating conditions at all speeds as compared to FLC except during the load perturbation where the performance is slightly decreased.

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