

ANFIS controller for vector control of three phase induction motor

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ABSTRACT

For variable speed drive applications such as electric vehicles, 3 phase induction motor is used and is controlled by fuzzy logic controllers. For the steady functioning of the vehicle drive, it is essential to generate required torque and speed during starting, coasting, free running, braking and reverse operating regions. The drive performance under these transient conditions are studied and presented. In the present paper, vector control technique is implemented using three fuzzy logic controllers. Separate Fuzzy logic controllers are used to control the direct axis current, quadrature axis current and speed of the motor. In this paper performance of the indirect vector controller containing artificial neural network based fuzzy logic (ANFIS) based control system is studied and compared with regular fuzzy logic system, which is developed without using artificial neural network. Data required to model the artificial neural network based fuzzy inference system is obtained from the PI controlled induction motor system. Results obtained in MATLAB-SIMULINK simulation shows that the ANFIS controller is superior compared to controller which is implemented only using fuzzy logic, under all dynamic conditions.

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1. INTRODUCTION

Squirrel cage induction motor is most suitable machine for variable speed drives, because of its robust nature in different operating conditions. To control the input voltage to the three-phase induction motor three phase PWM techniques are used. Scalar speed control techniques such as voltage control, v/f control provide satisfactory performance for steady state conditions [1]. But under dynamic conditions such as starting, sudden change in the load and speed reversal, the performance deteriorates. To respond for such transient conditions vector control techniques are used [2]. In vector controlled techniques using the suitable control algorithm, input voltage to the motor is adjusted so that required amount of direct and quadrature axis currents are drawn by the motor to meet the requirements of desired speed and torque. In flux oriented techniques induction motor will adopt the properties of separately excited dc motor, where speed and torque are controlled separately and there is no de-coupling between field and armature circuits [3]. To achieve decoupling of speed and torque control it is important to maintain phase difference of 90 degrees between stator direct axis current and stator quadrature axis current which are responsible to control speed and torque respectively. To maintain the values of these currents to desired values controller are used. These controllers require mathematical model of the motor and parameters of the squirrel cage induction motor to be perfectly determined [4]. But developing the exact model and identifying the instantaneous parameters of the machine are not possible due to change in the operating points under transient conditions [5]. Due to this the

conventional techniques such as P, PI, PID controllers used in the control of torque and speed does not provide the satisfactory performances [6-7]. To overcome the shortcomings of conventional techniques, non crisp techniques such as fuzzy logic controllers are used in control of currents and speed [8]. Fuzzy logic is used when one knows the system well and behavior of the system can be expressed by fuzzy rules developed using antecedents, consequents and conjunctions [9]. Similarly artificial neural network can be used to model a given system when one has input and output data sets but no knowledge of the system [10]. System is trained to learn the relationship between output and input variables. System is developed using neural network technique such that it performs well for seen or expected and unforeseen or unexpected data which will happen during steady state and dynamic states respectively [11]. By combining the features of fuzzy logic and neural network techniques a system or a controller can be developed which has a performance superior compared to only fuzzy logic system. This is called as adaptive Neuro-Fuzzy inference system [12]. Here to write the rules for fuzzy logic system neural network is used. When input and output relationship of a particular system is known neural network can be used to model the system. In this paper the available input-out data is used to identify corresponding fuzzy inference system for the controller. By combining the neural network and fuzzy logic tools, the positive features of both soft computing tools result in more intelligent controller. Compared to conventional control techniques, fuzzy logic based control techniques provide better performance of the induction motor since these controllers are robust to parameter changes taking place in the motor during transient like change in input voltage, change in load and speed reversal [13].

2. RESEARCH METHOD

In this section control strategy implemented in control of 3-phase induction motor drive is explained. Theoretical concepts used in implementation simulation model are focused.

2.1. Field oriented control of 3-phase asynchronous motor

Scalar control influenced control strategies controlling 3-phase induction motor have resulted in good steady-state responses but poor behavior at dynamic changes during its operation like starting, sudden increase of load torque and change in the direction of rotation. Air gap flux in the motor getting deviated from its set value is the main reason for its deteriorated performance under above said transient conditions [14]. In scalar control air gap flux is controlled only in terms of its magnitude. The phase of the control variable air gap flux was neglected. To control this air gap flux, stator currents of the motor are controlled. In order to accommodate both phase and magnitude, the control variable is seen as a space vector which has both magnitude and phase. Unlike DC motors 3 phase induction motor has only one circuit to control torque and speed [15]. To achieve a decoupled control, in control domain the motor is converted to two phase motor by taking the projections of flux on the orthogonal direct and quadrature axis using Clark's transformation. Since control of dc quantity is simpler compared to its ac counterpart, the 3 phase induction motor is modeled in synchronous rotating reference frame [16]. As the name suggest, in this reference frame the orthogonal quadrature and direct axes references rotate at the speed of flux resulting dc quantities. Induction motor is converted to rotating reference frame from its stationary reference using Park's transformation. This is called field oriented control. Control variables, direct and quadrature axis currents obtained in DC, two phase domain are converted back to ac three phase control parameters using the inverse Park and inverse Clark's transformations respectively.

2.2. Indirect vector control

For the realization of indirect vector control in Figure 1, 3-phase induction motor is modeled in synchronously rotating reference frame. As shown in (1) to (19) used to model the motor in required reference frame.

$$R_r i_{qr}^e + p \lambda_{qr}^e + \omega_{sl} \lambda_{dr}^e = 0 \quad (1)$$

$$R_r i_{dr}^e + p \lambda_{dr}^e - \omega_{sl} \lambda_{qr}^e = 0 \quad (2)$$

where:

$$\omega_{sl} = \omega_s - \omega_r \quad (3)$$

$$\lambda_{qr}^e = L_m i_{qs}^e + L_r i_{qr}^e \quad (4)$$

$$\lambda_{dr}^e = L_m i_{ds}^e + L_r i_{dr}^e \quad (5)$$

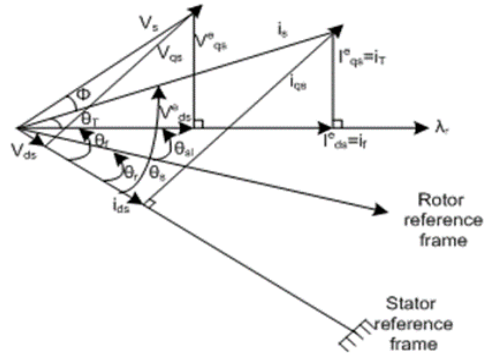


Figure 1. Vector controller phasor diagram

The symbols used in the equations are as follows. R_r represents rotor resistance per phase, L_m is used for mutual inductance per phase. L_r is used to represent self-inductance of rotor. i_{dr}^e and i_{qr}^e are reference current. ‘p’ indicates differential operator with respect to time, ω_{sl} and ω_r are slip speed and rotor speed respectively. Notations λ_{qr}^e and λ_{dr}^e represent rotor flux linkages in indicated reference frames [17]. Rotor flux linkage vector is aligned to direct axis, results in expressions shown.

$$\lambda_r = \lambda_{dr}^e \tag{6}$$

$$\lambda_{qr}^e = 0 \tag{7}$$

$$p\lambda_{qr}^e = 0 \tag{8}$$

Substituting above equations in motor model expressed in (1) and (2) can be expressed as,

$$R_r i_{qr}^e + \omega_{sl} \lambda_r = 0 \tag{9}$$

$$R_r i_{dr}^e + p\lambda_r = 0 \tag{10}$$

Rotor and stator currents are related as:

$$i_{qr}^e = \frac{-L_m}{L_r} i_{qs}^e \tag{11}$$

$$i_{dr}^e = \frac{\lambda_r}{L_r} - \frac{L_m}{L_r} i_{ds}^e \tag{12}$$

Expressions for field current and slip speed are represented as,

$$i_f = \frac{1}{L_m} [1 + T_r p] \lambda_r \tag{13}$$

$$\omega_{sl} = K_{it} \left[\frac{L_r}{T_r} \right] \left[\frac{T_e}{\lambda_r^2} \right]$$

$$K_{it} R_r \frac{T_e}{\lambda_r^2} = \frac{L_m}{T_r} \frac{i_T}{\lambda_r} \tag{14}$$

where:

$$i_f = i_{ds}^e \tag{15}$$

$$i_T = i_{qs}^e \tag{16}$$

$$T_r = \frac{L_r}{R_r} \tag{17}$$

$$K_{it} = \frac{2}{3} \frac{2}{P} \tag{18}$$

Developed electromagnetic torque is expressed as:

$$T_e = K_{te} \lambda_r i_T \tag{19}$$

where K_{te} is expressed as $K_{te} = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r}$

In indirect vector control method, the present location of flux is continuously monitored and compared with the reference space vector. The air gap flux is made to follow the reference flux vector by varying suitably the values of input voltage and frequency. The flux control is achieved by controlling the currents in two phase DC domain, as controlling in DC domain results in better performance as variable to be controlled will remain constant with respect to time. Figure 2 shows the flowchart for calculating desired values of currents in two phase domain. By making use of induction model and parameters, required values of stator currents to be maintained are calculated. The drive is made to follow these calculated values by using suitable control methods like PI, fuzzy logic and artificial neural network based fuzzy logic system. Figure 3 shows the representation of 3-phase induction motor drive using indirect vector control scheme. Three controllers are used to control speed, torque and field current. In the present work these controllers are ANFIS based fuzzy logic controllers. Inverter used to control both voltage and frequency of voltage input to the motor is controlled using space vector pulse width modulation method.

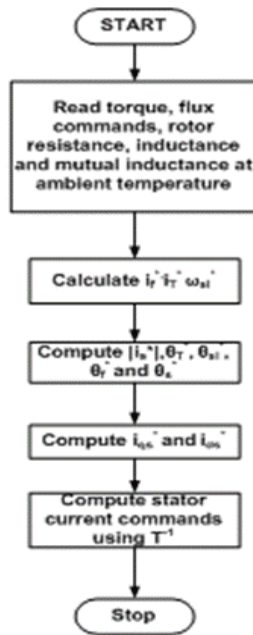


Figure 2. Flowchart for indirect vector control

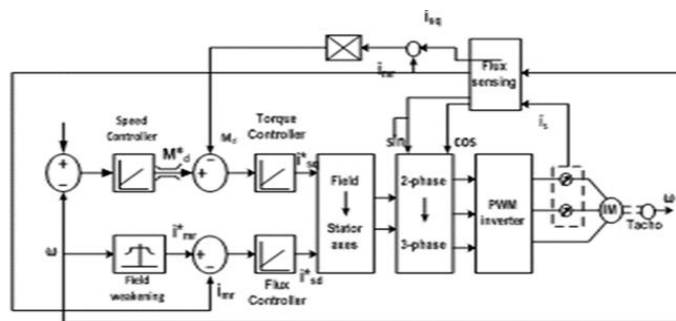


Figure 3. Block diagram of indirect vector control

2.3. Artificial neural network based FLC

In modeling and control of dynamic systems such as industrial motor drives, use of intelligent control techniques such as genetic algorithm, swarm intelligence technique, fuzzy logic and neural networks are used due to their improved performance over traditional techniques [18]. In the present paper ANFIS based controllers are used. To model a system using artificial neural network, one should have input-output data, which can be obtained by conducting practical experiments [19]. Fuzzy logic is a suitable method of modeling a system when one has complete knowledge about the functioning of a system but representing it with the help of equations is not possible. Fuzzification converts input and output variables, which are crisp in nature into fuzzy variables. A membership value is assigned to the members in the fuzzy set. In crisp set member will be either present or will not be present. In fuzzy set degree of belonging can vary from zero to one based on the belongingness of a member in the fuzzy set. In fuzzy logic system, fuzzification of variables will be based on expertise over the system [20]. Range selection of variables and number of membership functions for a variable decide the performance of the controller. Range can be either normalized to some base value or it can be used without normalizing. Number of membership functions for the variables depends on the numbers of rules to be written for representing a system [21]. Whereas in ANFIS range of the variables and their membership values are based on the data presented to training system. ANFIS and PI controllers are used to control the asynchronous motor. MATLAB-SIMULINK is used to implement entire drive system. Three controllers required in implementation of vector control monitor and maintain speed, direct and quadrature axis currents to required level [22-23]. In the present paper current control is achieved using proposed ANFIS controllers and speed is controlled using a PI controller. In ANFIS model for controllers, error and change in error are input variables and output variables are quadrature and direct axis current respectively. The data used in ANFIS model is obtained from a MATLAB simulation, where PI controller is used in all the three controllers. Since the ANFIS has a property of generalization, it responds well for the unseen data also, and performance is superior compared to only fuzzy logic controllers. Inference method used in the ANFIS model is Takagi-Sugeno type. In implementation of ANFIS model, rules which are linguistic in nature, relate antecedent with consequents. Antecedent and consequents are membership functions of input and output variables respectively. The amount of knowledge that can be embedded in a fuzzy logic based controller is directly proportional to number of rules. Less number of rules can only represent partial knowledge of an expert. For the ANFIS controllers used in indirect vector control, set of 9 rules, 25 rules and 49 rules are used. Performance with respect to rise time, steady state error, etc improves for increase in number of rules [24].

2.4. Implementation using MATLAB-SIMULINK

Entire motor drive system for electric vehicle is realized in Matlab-Simulink. Different subsystems taking care of specific functions like 3-phase to 2-phase conversion, 2-phase to 3-phase conversion, stator to field reference axis, field reference to stator reference frame, speed control, torque control, command speed are combined to integrate the system [25]. Induction motor parameters are given in Table 4. In this simulation study, performances of the motor under different transient conditions are monitored for FLC and ANFIS controllers. In each case, i.e. for fuzzy logic controllers and ANFIS controllers, performance parameters are tabulated for 9, 25 and 49 number of rules [26]. Error and change in error are input variables used in the model of the current controllers. In 9 rule FLC, three membership functions are used for both input and output variables are negative, zero and positive. Membership functions and rules used in 9 rules, 25 rules and 49 rules fuzzy logic controllers are shown in Tables 1, 2 and 3 respectively.

Table 1. 9 Rule fuzzy logic controller

ceé	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Table 2. 25 Rule fuzzy logic controller

ceé	NL	NMA	Z	PBA	PL
NL	NL	NL	NL	NA	Z
NBA	NL	NA	NBA	Z	PA
Z	NL	NBA	Z	PBA	PL
PBA	NBA	Z	PBA	PA	PL
PL	Z	PA	PL	PL	PL

Table 3. 49 Rule fuzzy logic controller

ceé	NL	NA	NBA	Z	PBA	PA	PL
NL	NL	NL	NL	NL	NA	NBA	Z
NA	NL	NL	NL	NA	NBA	Z	PBA
NBA	NL	NL	NA	NBA	Z	PBA	PA
Z	NL	NA	NBA	Z	PBA	PA	PL
PBA	NA	NBA	Z	PBA	PA	PL	PL
PA	NBA	Z	PBA	PA	PL	PL	PL
PL	Z	PBA	PA	PL	PL	PL	PL

Table 4. Induction motor parameters

Stator Resistance	0.277Ω
Rotor Resistance	0.183Ω
Stator Inductance	0.0553H
Rotor Inductance	0.056H
Mutual Inductance	0.0538H
Moment of Inertia	0.0165Kg.M ²
Viscous Friction	0.05Nms/rad
No. of pole pairs	2

3. RESULTS AND ANALYSIS

Figures 4-6 shows response of the system for 9, 25 and 49 rule ANFIS systems. Analysis of performance of fuzzy logic controllers and ANFIS controllers used in 3-phase Induction motor vector control is as shown in Table 5 and Table 6. Transients are introduced to the motor drive by the actions of starting, reversal of speed, increase in load and decrease in the load by changing the command speed and command load torque values. Fuzzy logic controller and artificial neural network based fuzzy logic controllers implemented using different number of rules such as 9, 25 and 49 are analyzed in terms of their rise time, steady state error, overshoot etc. At starting speed command is changed from 0 to 100 radians per second, Increase in load is achieved by changing the command torque from zero to 5 N-m, decrease in the load is realized by changing the command torque from 5 N-m to 0 N-m and speed reversal is incorporated by changing the speed command from 100 Rad/s to -100 Rad/s. In MATLAB simulation of proposed 3-phase Induction motor drive, dynamics such as starting, increase in load, decrease in load and speed reversal are introduced at 0.5 second, 1 second, 1.3 seconds and 1.8 seconds respectively. By observing the waveforms of motor speed and electromagnetic torque developed, system performance parameters are tabulated for 9 rules, 25 rules and 49 rules fuzzy logic controller and ANFIS controller. From the performance parameters tabulated in Table 5 and Table 6, it can be found that response of the system improves with increase in number of rules and ANFIS controller has improved performance to its corresponding fuzzy logic controller.

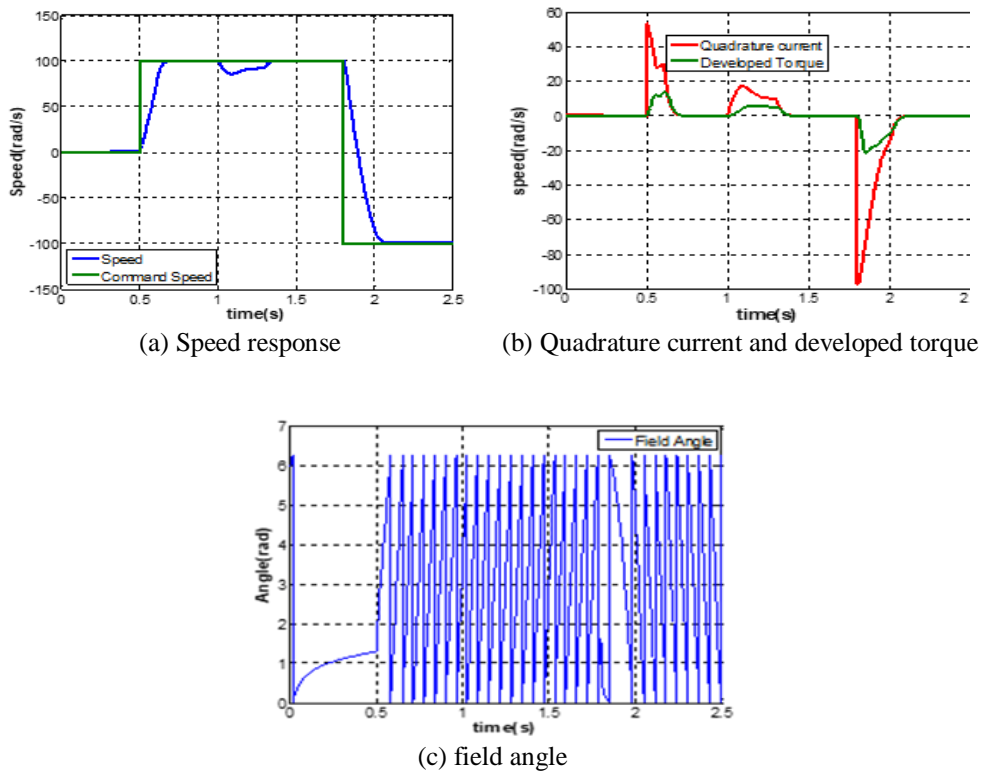
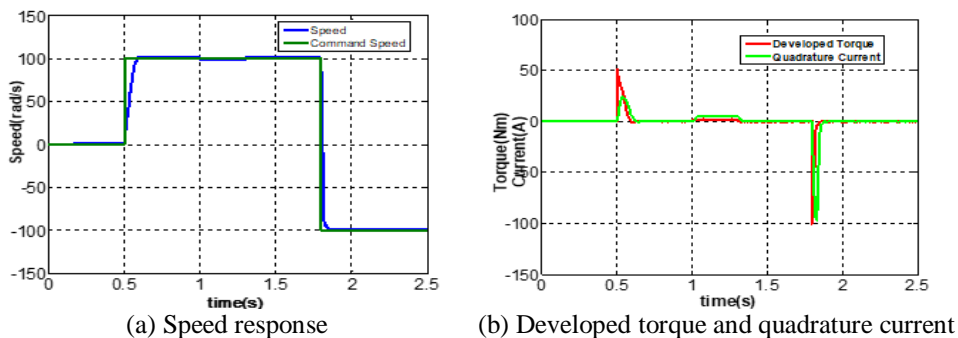


Figure 4. 9 rules ANFIS FLC



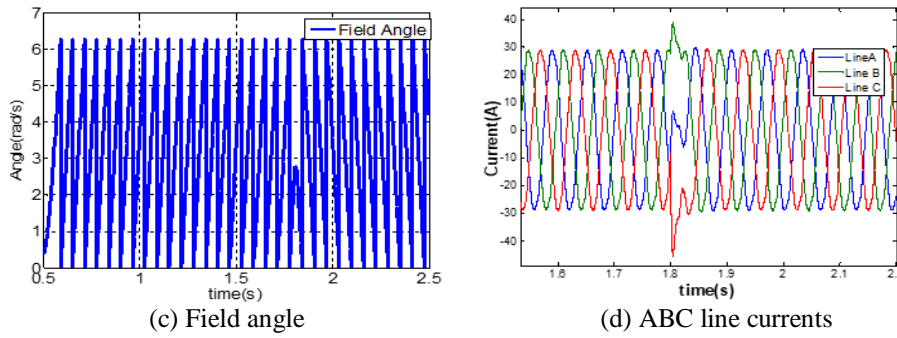


Figure 5. 25 rule ANFIS

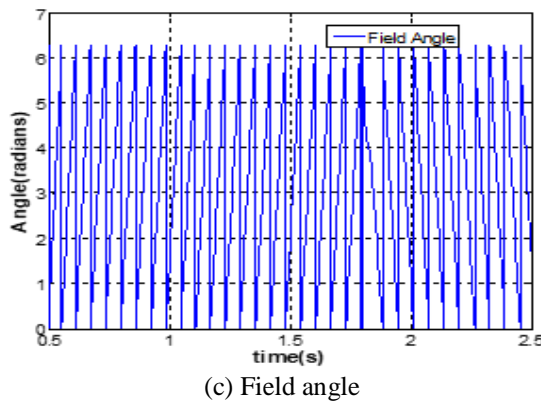
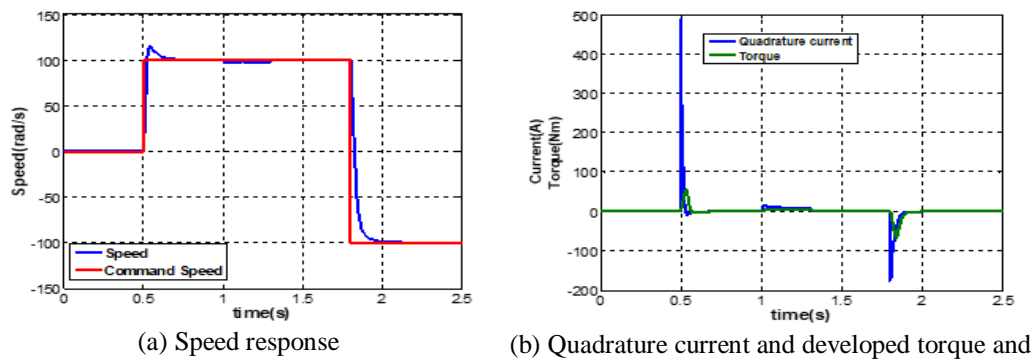


Figure 6. 49 rule ANFIS

Table 5. Speed response

Speed control performance			9 rules	25 rules	49 rules
Starting	Rise time (ms)	FLC	100	90	60
		ANFIS	87.4	59	17.4
	Steady state error (rad/s)	FLC	0	0	0
		ANFIS	1.2	0.8	0.204
Overshoot (rad/s)		FLC	0.8	1.176	1.2
		ANFIS	0	1.6	15
Speed Reversal	Rise time (ms)	FLC	240	220	200
		ANFIS	169.1	17.3	53.9
	Steady state error (rad/s)	FLC	0	0	0
		ANFIS	-1.32	-1	-0.24
Overshoot (rad/s)		FLC	0.8	1.176	1.275
		ANFIS	0	0	0

Table 6. Torque response

Torque control performance			9 rules	25 rules	49 rules
Load torque of 5 N-m applied at 1s	Rise time (ms)	FLC	11	90	60
		ANFIS	126.7	29.9	30.3
	Steady state error (rad/s)	FLC	0.1	0.05	0.1
		ANFIS	0.9	0.1	0.01
Overshoot (rad/s)		FLC	2.7	2	1.56
		ANFIS	0	0.2	0.2
Load torque reduced from 5 N-m to 0 N-m at 1.3s	Rise time (ms)	FLC	240	220	200
		ANFIS	131.3	28.3	30.7
	Steady state error (rad/s)	FLC	0	0	0
		ANFIS	0	0.02	0
Overshoot (rad/s)		FLC	0.4	1.3	1.3
		ANFIS	0	0.1	0

4. CONCLUSION

To satisfy the requirements of electric vehicle drive consisting of asynchronous motor, fuzzy logic and ANFIS based vector controller is implemented. Quadrature and Direct axis current controllers used in indirect vector control are implemented using fuzzy logic controllers and ANFIS based controllers. Analysis of the fuzzy logic controller and proposed ANFIS controller is made for different dynamic conditions and for different number of rules in the rule base. It can be concluded from the results obtained and as tabulated in Tables 5 and 6 that ANFIS based controller performs better over fuzzy logic controllers. It is also clear from the results that in both fuzzy logic controller and ANFIS based controllers performance improves with increase in the number of rules. The performance parameters are analysed during the starting, speed reversal and change in load torque on the electric vehicle drive.

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