A COMPARATIVE PERFORMANCE ANALYSIS OF ARTIFICIAL INTELLIGENCE TECHNIQUES FOR INDUCTION MOTOR DRIVE

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Abstract: *The paper presents various Artificial Intelligent controllers like ANN, Fuzzy controller, ANFIS, Fuzzy Neural Controller applied to induction motor drive system. Artificial Intelligent Controller (AIC) could be the best controller for Induction Motor control. This is because that AIC possess advantages as compared to the conventional PI, PID and their adaptive versions. During the operation of induction motor, even when the parameters and load of the motor varies, a desirable control performance in both transient and steady states must be provided. Therefore, control strategy must be robust and adaptive. Speed control of induction motor can achieve maximum torque and efficiency by using artificial intelligent techniques. But, the main problem with the conventional, fuzzy controllers is that the parameters associated with the membership functions and the rules depend broadly on the intuition of the experts. The comparison of dynamic performance of induction motor is also investigated by using Conventional, Fuzzy, Neural, ANFIS and Fuzzy Neural controllers.*

Key words: *Fuzzy Logic Controller (FLC), Fuzzy Neural Network (FNN), Neural Network (NNW), Adaptive Neuro-Fuzzy Inference System (ANFIS).*

I. INTRODUCTION

Induction motors play a vital role in the industrial sector especially in the field of electric drives & control. Without proper controlling of the speed, it is virtually impossible to achieve the desired task for a specific application. AC motors, particularly the Squirrel-Cage Induction Motors (SCIM), enjoy several inherent advantages like simplicity, reliability, low cost and virtually maintenance-free electrical drives. However, for high dynamic performance industrial applications, their control remains a challenging problem because they exhibit significant nonlinearities and many of the parameters, mainly the rotor resistance, vary with the operating conditions. Field Orientation Control (FOC) or vector control of an induction machine achieves decoupled torque and flux dynamics leading to independent control of the torque and flux as far as separately excited DC motor is considered. FOC methods are attractive, but suffer from one major disadvantage. They are sensitive to motor parametric variations such as the rotor time constant and an incorrect flux measurement or estimation at low speeds. Consequently, performance deteriorates and a conventional controller such as a PID is unable to maintain satisfactory performance under these conditions. Recently, there has been an increasing interest in combining artificial intelligent control tools with classical control techniques. The principal motivations for such a hybrid implementation is that with fuzzy logic, neural networks & rough sets issues, such as uncertainty or unknown variations in plant parameters and structure can be dealt with more effectively, hence improving the robustness of the control system[1-6]. Conventional controls have on their side well established theoretical backgrounds on stability and allow different design objectives such as steady state and transient characteristics of the closed loop system to be specified. Several works were contributed to the design of such hybrid control schemes which was shown by various researchers. Classical control systems like PI, PID control have been used, together with vector control methods, for the speed control of induction machines by various researchers. The main drawbacks of the linear control approaches were the sensitivity in performance to the system parameters variations and inadequate rejection of external perturbations and load changes. Intelligent, self-learning or self-organizing controls using expert systems, artificial intelligence, fuzzy logic, neural networks, hybrid networks, etc, have been recently recognized as the important tools to improve the performance of the power electronics based drive systems in the industrial sectors. Combination of this intelligent control with the adaptiveness appears today as the most promising research area in the practical implementation & control of electrical drives. With the advent of artificial intelligent techniques, these drawbacks can be mitigated. One such technique is the use of Fuzzy Logic in the design of controller either independently or in hybrid with PI controller. Fuzzy Logic Controller yields superior and faster control, but main design problem lies in the determination of consistent and complete rule set and shape of the membership functions. A lot of trial and error has to be carried out to obtain the desired response which is time consuming. On the other hand, ANN alone is insufficient if the training data are not enough to take care of all the operating modes. The draw-backs of Fuzzy Logic Control and Artificial Neural Network can be overcome by the use of Adaptive Neuro-Fuzzy Inference System[7-14].

II. Dynamic Modeling & Simulation of Induction Motor Drive

The induction motors dynamic behavior can be expressed by voltage and torque which are time varying. The differential equations that belong to dynamic analysis of induction motor are so sophisticated. Then with the change of variables the complexity of these equations decrease through movement from poly phase winding to two phase winding (q-d). In other words, the stator and rotor variables like voltage, current and flux linkages of an induction machine are transferred to another reference model which remains stationary [1-6].

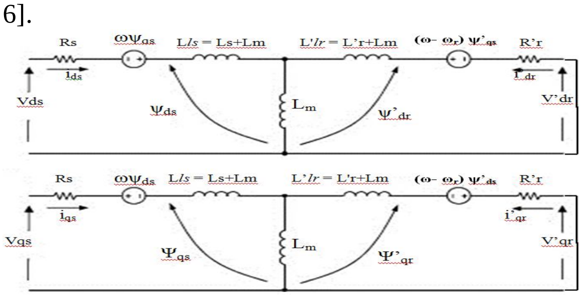


Fig.1 d q Model of Induction Motor.

In Fig. 1 stator inductance is the sum of the stator leakage inductance and magnetizing inductance (Lls = Ls + Lm), and the rotor inductance is the sum of the rotor leakage inductance and magnetizing inductance (Llr = Lr + Lm). From the equivalent circuit of the induction motor in d-q frame, the model equations are derived. The flux linkages can be achieved as:

$$\frac{1}{\omega_b}\frac{d\psi_{qs}}{dt} = v_{qs} - \frac{\omega_e}{\omega_b}\psi_{ds} - R_s i_{qs} \quad (1)$$

$$\frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} = v_{ds} - \frac{\omega_e}{\omega_b}\psi_{qs} - R_s i_{ds} \quad (2)$$

$$\frac{1}{\omega_b}\frac{d\psi_{qr}}{dt} = v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{dr} - R_s i_{qr} \quad (3)$$

$$\frac{1}{\omega_b}\frac{d\psi_{dr}}{dt} = v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{qr} - R_s i_{dr} \quad (4)$$

By substituting the values of flux linkages in the above equations, the following current equations are obtained as:

$$i_{qs} = \frac{(\psi_{qs} - \psi_{mq})}{X_{ls}} \quad (5)$$

$$i_{ds} = \frac{(\psi_{ds} - \psi_{md})}{X_{ls}} \quad (6)$$

$$i_{qr} = \frac{(\psi_{qr} - \psi_{mq})}{X_{ls}} \quad (7)$$

$$i_{dr} = \frac{(\psi_{dr} - \psi_{md})}{X_{ls}} \quad (8)$$

where ψmq and ψmd are the flux linkages over Lm in the q and d axes. The flux equations are written as follows:

$$\psi_{mq} = X_{ml}\left(\frac{\psi_{qs}}{X_{ls}} + \frac{\psi_{qr}}{X_{lr}}\right) \quad (9)$$

$$\psi_{md} = X_{ml}\left(\frac{\psi_{ds}}{X_{ls}} + \frac{\psi_{dr}}{X_{lr}}\right) \quad (10)$$

$$X_{ml} = \frac{1}{\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}} \quad (11)$$

In the above equations, the speed ωr is related to the torque by the following mechanical dynamic equation a

$$T_e = T_{load} + J\frac{d\omega_m}{dt} = T_{load} + \frac{J2}{p}\frac{d\omega_r}{dt} \quad (12)$$

then ωr is achievable from above equation, where:
p: number of poles.
J: moment of inertia (kg/m2).

In the previous section, dynamic model of an induction motor is expressed. The model constructed according to the equations has been simulated by using MATLAB/SIMULINK as shown in Fig.2 in conventional mode of operation of induction motor. A 3 phase source is applied to conventional model of an induction motor and the equations are given by:

$$V_a = \sqrt{2}\,V_{rms}\sin(\omega t) \quad (13)$$

$$V_b = \sqrt{2}\,V_{rms}\sin\left(\omega t - \frac{2\pi}{3}\right) \quad (14)$$

$$V_c = \sqrt{2}\,V_{rms}\sin\left(\omega t + \frac{2\pi}{3}\right) \quad (15)$$

By using Parks Transformation, voltages are transformed to two phase in the d-q axes, and are applied to induction motor. In order to obtain the stator and rotor currents of induction motor in two phase, Inverse park transformation is applied in the last stage [6,11].

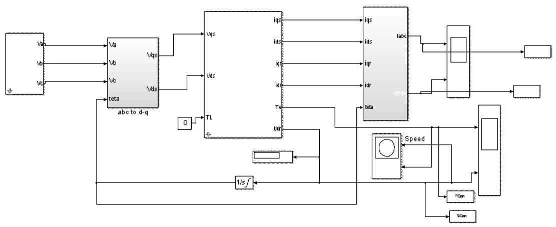


Fig. 2 Simulated Induction Motor Model in Conventional Mode.

III. ARTIFICIAL INTELLIGENT CONTROLLER

Despite the great efforts devoted to induction motor control, many of the theoretical results cannot be directly applied to practical systems. The difficulties that arise in induction motor control are complex computations, model nonlinearity and uncertainties in machine parameters. Recently, intelligent techniques are introduced in order to overcome these difficulties.

Intelligent control of induction motor refers to the control of an induction motor drive using artificial intelligence techniques such as Fuzzy, Neural, ANFIS and Fuzzy Neuro Network[15-20]. Various artificial intelligent controllers are as follows:

(a) Fuzzy Logic Controller: The speed of induction motor is adjusted by the fuzzy controller. The fuzzy rules decision implemented into the controller is given in Table-I.

Table I. Modified Fuzzy Rule Decision.

		Δ_e				
		NB	NS	ZZ	PS	PB
	PB	ZZ	NS	NS	NB	NB
e	PS	PS	ZZ	NS	NS	NB
	ZZ	PS	PS	ZZ	NS	NS
	NS	PB	PS	PS	ZZ	NS
	NB	PB	PB	PS	PS	ZZ

The conventional simulated induction motor model is shown in Fig. 2 and it is further modified by adding Fuzzy controller as shown in Fig. 3. Speed output terminal of induction motor is applied as an input to fuzzy controller, and in the initial start of induction motor the error is maximum, so according to fuzzy rules FC produces a crisp value. Then this value will change the frequency of sine wave in the speed controller. The sine wave is then compared with triangular waveform to generate the firing signals of IGBTs in the PWM inverters. The frequency of these firing signals also gradually changes, thus increasing the frequency of applied voltage to Induction Motor [20].

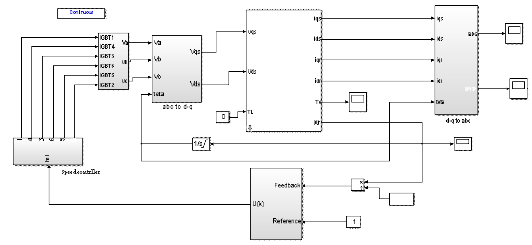


Fig. 3 Fuzzy Control Induction Motor Model.

As discussed earlier, the crisp value obtained from Fuzzy Logic Controller is used to change the frequency of gating signals of PWM inverter. Thus, the output AC signals obtained will be variable frequency sine waves. The sine wave is generated with amplitude, phase and frequency which are supplied through a GUI. Then the clock signal which is sampling time of simulation is divided by crisp value which is obtained from FLC. So by placing three sine waves with different phases, one can compare them with triangular waveform and generate necessary gating signals of PWM inverter. So, at the first sampling point the speed is zero and error is maximum. Then whatever the speed rises, the error will decrease, and the crisp value obtained from FLC will increase. So, the frequency of sine wave will decrease which will cause IGBTs switched ON and OFF faster. It will increase the AC supply frequency, and the motor will speed up. Fig.3 shows Fuzzy logic controller. The inputs to these blocks are the gating signals which are produced in speed controller block[]. The firing signals are applied to IGBT gates that will turn ON and OFF the IGBTs.

*(b) Artificial Neural Network (ANN):*The most important feature of Artificial Neural Networks (ANN) is its ability to learn and improve its operation using neural network training [7-8]. The objective of Neural Network Controller(NNC) is to develop a back propagation algorithm such that the output of the neural network speed observer can track the target one i.e., speed. It can be seen that the d axis and q axis voltage equations are coupled by the terms dE and qE. These terms are considered as disturbances and are cancelled by using the proposed decoupling method. If the decoupling method is implemented, the flux component equations become

$$\Phi_{dr} = G(s)v_{ds}$$

$$\Phi_{qr} = G(s)v_{qs}$$

Large values of η may accelerate the ANN learning and consequently fast convergence is obtained, but may cause oscillations in the network output, whereas low values will cause slow convergence. Therefore, the value of η has to be chosen carefully to avoid instability [18]. The proposed neural network controller is shown in Fig.4[23].

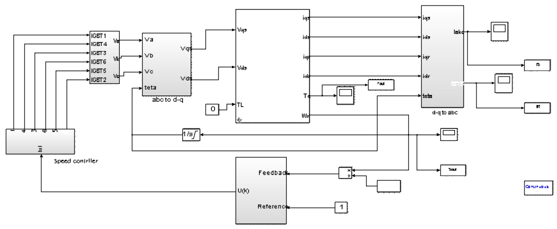


Fig. 4 Neuro controller based induction motor drive.

(c) Adaptive Neuro Fuzzy Inference System (ANFIS) Controller:AC motor drives are used in multitude of industrial and process applications requiring high performances. In high performance drive systems, the motor speed should closely follow a specified reference trajectory regardless of any load disturbances and any model uncertainties. In the designing of a controller, the main criteria is the controllability of torque in an induction motor with good transient and steady state responses. With certain drawbacks, PI controller is able to achieve these characteristics. The main drawbacks are (i) The gains cannot be increased beyond certain limit. (ii) Non linearity is introduced, making the system more complex for analysis. With the advent of artificial intelligent techniques, these drawbacks can be mitigated. One such technique is the use of Fuzzy Logic in the design of controller either independently or in hybrid with PI controller. Adaptive Neuro-Fuzzy Inference System(ANFIS) replaces the draw-backs of Fuzzy Logic Control and Artificial Neural Network. Adaptive neuro fuzzy combines the learning power of neural network with knowledge representation of fuzzy logic. Neuro fuzzy techniques have emerged from the fusion of Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS) and have become popular for solving the real world problems[18-20]. A neuro fuzzy system is based on a fuzzy system which is trained by a learning algorithm derived from neural network theory. There are several methods to integrate ANN and FIS and very often the choice depends on the applications. In this paper, the inputs will be e(k) and Δe(k)[12,15,17]. The learning algorithm applied to this model is Hebbian. This method is feed forward and unsupervised and the weights will be adjusted by the following formula:

$$w_i(new) = w_i(old) + x_i y \qquad (21)$$

The ANFIS layout is shown in Fig.5. It states that if the cross product of output and input is positive, then it results in increase of weight, otherwise decrease of weight. In layer 2 of ANFIS layout, the triangular membership function is same as that of the fuzzy controller model. The output of layer 2 is given by:

$$O_2 = \mu_1 . \mu_2 . \mu_3 \qquad (22)$$

Layer 3 indicates the pro (product) layer and its output is product of inputs, which is given by:

$$O_3 = \mu_i(e) . \mu_j(\Delta e) \qquad (23)$$

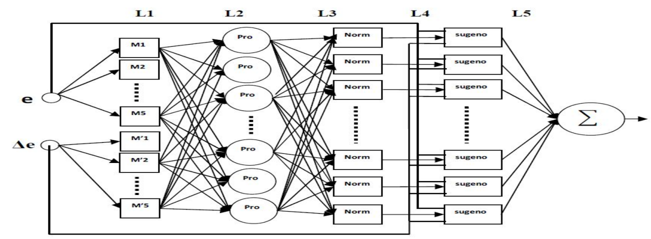


Fig. 5 ANFIS layout

Layer 4 represent Norm and it calculates the ratio of ith firing strength to sum of all firing strengths. The obtained output is normalized firing strength, which is given by:

$$O_4 = \frac{w_i}{\sum w} \qquad (24)$$

Layer 5 is an adaptive node with functionality as follows:

$$O_5 = w_i f_i = w_i(p_i(e) + q_i(\Delta e) + r_i) \qquad (25)$$

That pi, qi, ri are consequent parameters, which are initially are set to 0.48, 0.25 and 1 respectively. Then they are adaptively adjusted with Hebbian learning algorithm. Layer 6 calculates the output which is given by :

$$O_6 = \frac{\sum w_i f_i}{\sum w_i} \qquad (26)$$

Fig. 6 shows the overall structure of Adaptive Neuro-Fuzzy model.

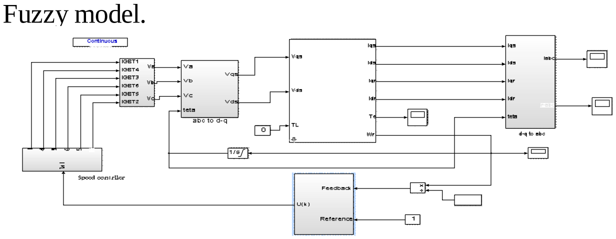


Fig.6 Adaptive Neuro-Fuzzy Controller Simulation model

*(d) Fuzzy Neural Network Controller(FNN):*During the last decades, fuzzy and neural network systems individually have reached a degree of maturity where they are applied to various real life applications. At present there is no generally accepted methodology for design of neural networks and uses only trial and error method which depends on the intuition of the designer. FNN has been proven a matured technique for control system design. FNN hybrid system which fuses fuzzy control and neural network have been propounded for utilising numerical data. NN model learns using numerical data as well as expert knowledge represented by fuzzy. Fuzzy logic is a

natural mechanism for propagating uncertainty. FNN models have potential for parallel computation with high flexibility. In this system neural network is implemented by the function of fuzzy system. First fuzzification of crisp input data is performed, second; fuzzy rule is implemented and finally the operation of defuzzification is performed to provide crisp output data. The fuzzy neural network implemented is shown in Figure7. In FNN linguistic statements are the inputs to multilayer neural network through fuzzy interface. The rest of the process is same as normal for fuzzy and neural. The simulated FNN controller is shown in Figure7 [23-27].

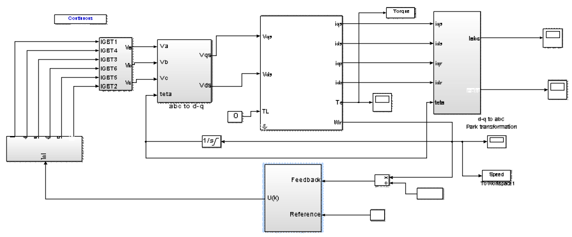


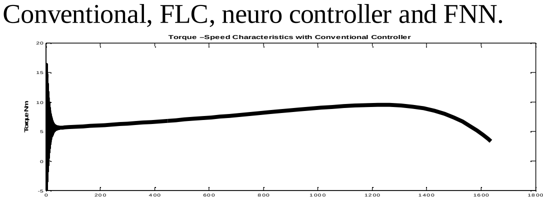
Fig..7. Fuzzy Neural Network Controller.

IV. COMPARTIVE ANALYSIS

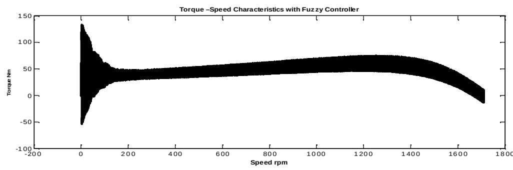
A complete simulation model for Induction motor drive incorporating Conventional, Fuzzy Logic Controller, Neural network controller, ANFIS and Fuzzy Neuro controller has been developed. Induction motor drive with Fuzzy controller is designed by proper adjustments of membership functions and Neural network controller is designed by adjusting the weights in order to get simulated results. Adaptive Neuro-Fuzzy Inference System (ANFIS) replaces the draw-backs of Fuzzy Logic Control and Artificial Neural Network. Adaptive neuro fuzzy combines the learning power of neural network with knowledge representation of fuzzy logic. FNN uses fuzzy operators and connectives in the mathematical operation of neural network to produce simulation results. The performance of the artificial intelligent based induction motor drive is investigated at different operating conditions. In order to prove the superiority of the ANFIS, a comparison is made with the response of conventional, FLC, NN and FNN based induction motor drive. The parameters of the induction motor considered in this study are summarized in Appendix ‘A’. The performances of the induction motor with all intelligent controllers are presented at no load and with load. The dynamic behaviours of the conventional controller, FLC controller, Neuro Controller, ANFIS and FNN are shown in Fig.2, Fig.4,Fig.6 and Fig 7 at no load and at load conditions respectively.

(a) At No load conditions:

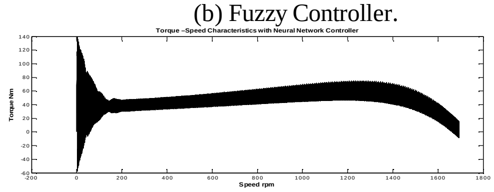
Modelling and simulation of Induction motor in conventional, fuzzy and adaptive neuro fuzzy are done on MATLAB/SIMULINK. A complete simulation model and dynamic performance for inverter fed induction motor drive incorporating the proposed FLC, neuro fuzzy controller, ANFIS and Fuzzy Neuro controller has been developed. The proposed ANFIS and fuzzy neuro controller is proved to be more superior as compared with the response of conventional, FLC, neuro speed controller based IM drive. Fig.8, 9 and 10 show the torque–speed characteristics, torque and speed responses of conventional, FLC, neuro controller, ANFIS and fuzzy neuro controller respectively. It appears that the rise time drastically decreases when Adaptive neuro fuzzy controller and FNN is added to simulation model and both the results are taken in same period of time. In fuzzy neural network based simulation, it is apparent from the simulation results shown in Fig.8(d) and Fig.8 (e), torque-speed characteristics converge to zero in less duration of time when compared with conventional Controller and FLC, which is shown in Fig.8(a), Fig.8 (b) and Fig.8(c). ANFIS controller has less overshoot and settles faster in comparison with FLC, Neuro controller and FNN. It is also noted that there is no steady-state error in the speed response during the operation when ANFIS controller is activated. In conventional controller, oscillations occur, whereas in fuzzy neuro, neuro controller, ANFIS and FLC, no oscillations occur in the torque response before it finally settles down as shown in Fig.9. Good torque response is obtained with fuzzy neuro, Neuro controller & ANFIS as compared to conventional and FLC at all time instants and it is observed that speed response is better than conventional controllers, FLC and neuro controller. There is a negligible ripple in speed response with ANFIS controller in comparison with conventional controller, FLC, neuro controller and FNN under dynamic conditions which are shown in Figure10. With the ANFIS controller, speed reaches its steady state value faster as compared to Conventional, FLC, neuro controller and FNN.



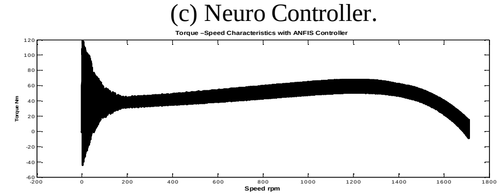
(a) Conventional Controller.



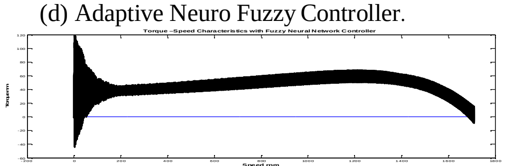
(b) Fuzzy Controller.



(c) Neuro Controller.

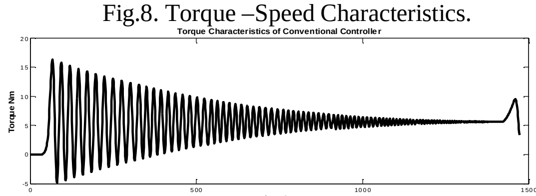


(d) Adaptive Neuro Fuzzy Controller.

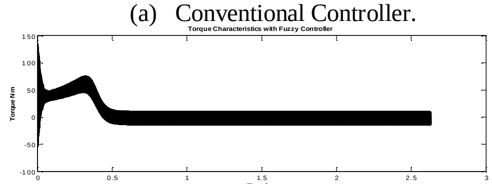


(e) Fuzzy Neuro Controller.

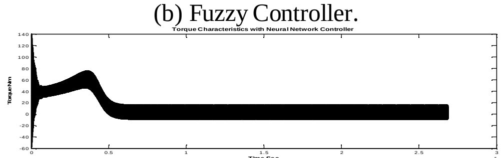
Fig.8. Torque –Speed Characteristics.



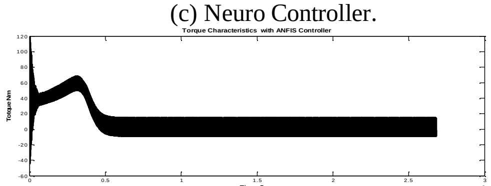
(a) Conventional Controller.



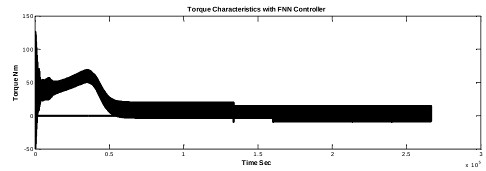
(b) Fuzzy Controller.



(c) Neuro Controller.

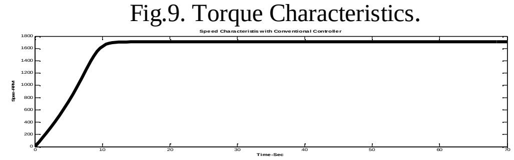


(d) Adaptive Neuro Fuzzy Controller.

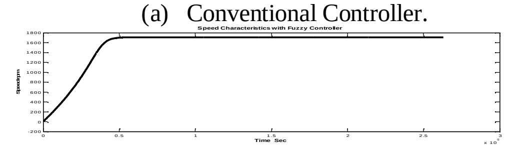


(e) Fuzzy Neuro Controller.

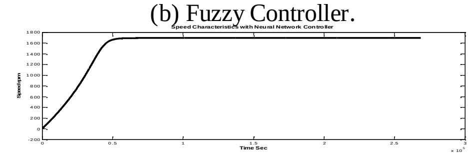
Fig.9. Torque Characteristics.



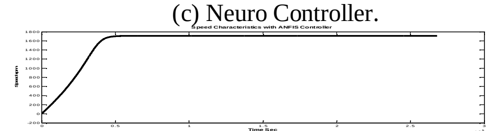
(a) Conventional Controller.



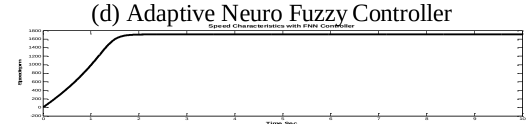
(b) Fuzzy Controller.



(c) Neuro Controller.



(d) Adaptive Neuro Fuzzy Controller

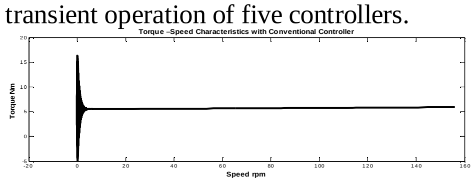


(e) Fuzzy Neuro Controller.

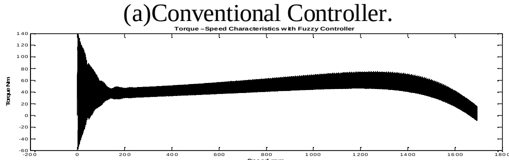
Fig.10. Speed Characteristics.

(b) At load conditions:

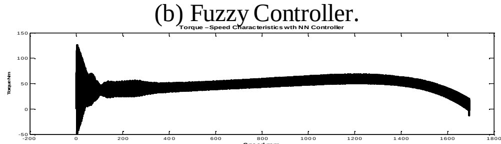
Induction motor drive with conventional controller speed response has small peak, but in case of fuzzy controller, neural network ANFIS and FNN speed response, it is quick and smooth response which is shown in Fig. 13. Fig.11, Fig.12 and Fig.13 show the waveforms of torque –speed, torque and speed characteristics with five controllers. Fig.13 shows the speed response with load torque using the conventional, fuzzy, neuro, ANFIS and fuzzy neuro controller respectively. The time taken by the conventional controlled system to achieve steady state is much higher than ANFIS and fuzzy neuro controlled system. The motor speed follows its reference with zero steady-state error and a fast response using a ANFIS Controller. On the other hand, the conventional controller shows steady-state error with a high starting current. It is to be noted that the speed response is affected by application of load. This is the drawback of a conventional controller with load. It is to be noted that the ANFIS and neuro controller gives better responses in terms of overshoot, steady-state error and fast response when compared with conventional and fuzzy. It also shows that the ANFIS controller based drive system can handle the sudden increase in command speed quickly without overshoot, under- shoot, and steady-state error, whereas the conventional and fuzzy controller-based drive system has steady-state error and the response is not as fast as compared to neuro and fuzzy neuro. Thus, the proposed ANFIS based drive has been found superior when compared with the conventional controller, FLC neuro controller and FNN controller. Table II and III present the performance comparison during steady state operation and transient operation of five controllers.



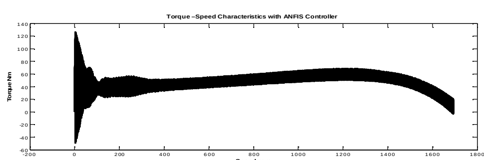
(a)Conventional Controller.



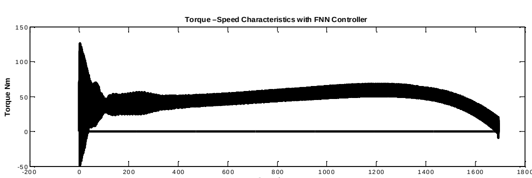
(b) Fuzzy Controller.



(c) Neuro Controller.

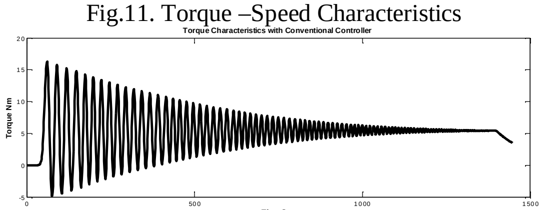


(d) Adaptive Neuro Fuzzy Controller

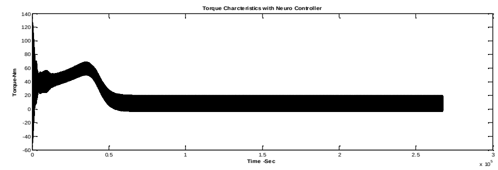


(e) Fuzzy Neuro Controller.

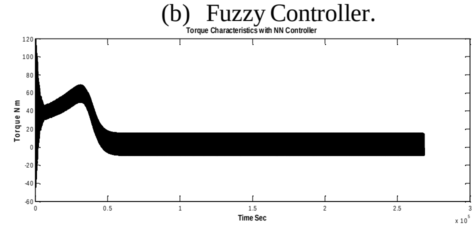
Fig.11. Torque –Speed Characteristics



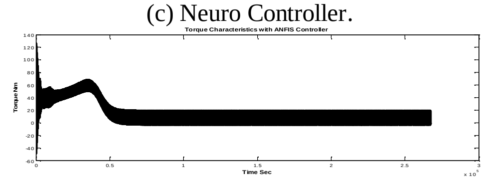
(a) Conventional Controller.



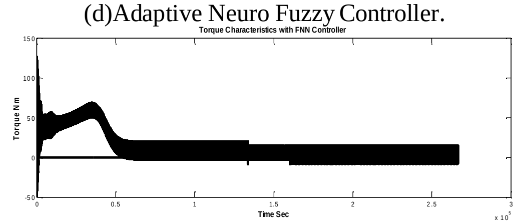
(b) Fuzzy Controller.



(c) Neuro Controller.

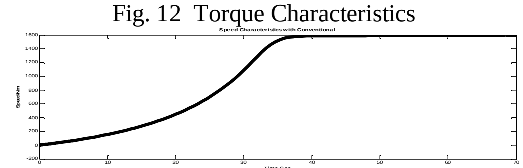


(d)Adaptive Neuro Fuzzy Controller.

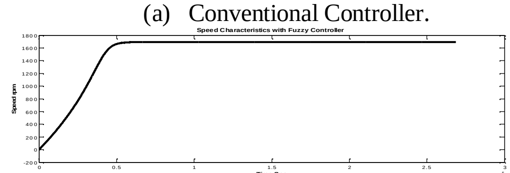


(e) Fuzzy Neuro Controller.

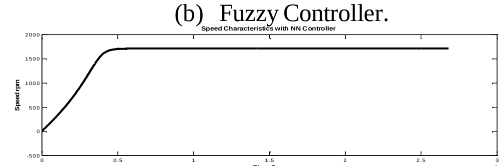
Fig. 12 Torque Characteristics



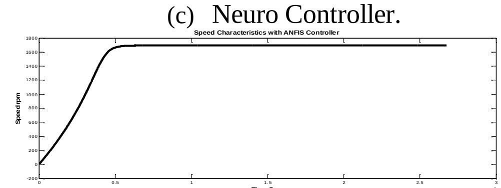
(a) Conventional Controller.



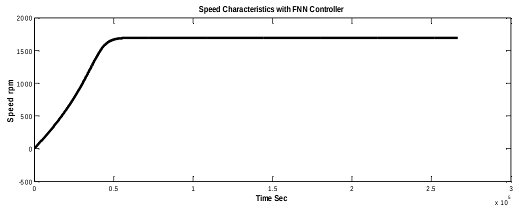
(b) Fuzzy Controller.



(c) Neuro Controller.



(d)Adaptive Neuro Fuzzy Controller.



(e) Fuzzy Neuro Controller.

Fig.10. Speed Characteristics.

Table -II

Performance Comparison Between Conventional, Fuzzy, Neural And Fuzzy Neuro Controllers During Steady State Operation.

Control strategies	Rise Time(sec)	Overshoot	Settling Time (sec)
Conventional	7.346	Yes	14.89
FLC	1.21	0.505	0.9615
ANN	1.209	0.505	0.7612
ANFIS	1.209	0.05	0.7612
FNN	1.209	0.498	0.7613

Table –III

Performance Comparison Between Conventional, Fuzzy, Neural And Fuzzy Neuro Controllers During Transient Operation

Control strategies	Rise Time(sec)	Overshoot	Settling Time(sec)
Conventional	4.461	Yes	10
FLC	1.279	0.521	0.8982
ANN	1.332	0.505	0.8151
ANFIS	1.332	0.505	0.8151
FNN	1.232	0.504	0.8154

IV. CONCLUSION

An Artificial intelligent based induction motor has been presented in this paper. The control strategy is developed with Fuzzy logic, Neural network, fuzzy neuro and ANFIS. The conventional control induction motor is compared with the proposed artificial intelligence based controllers, and their performance with fuzzy, neural network, ANFIS and fuzzy neuro controllers is better than conventional controller. The comparative results prove that the performance of induction motor drive with neuro controller, ANFIS and fuzzy neuro is proved to be superior to that with conventional controller and fuzzy controller. Thus, by using ANFIS and neuro controller, the transient response of induction machine has been improved greatly and the dynamic response of the same has been made faster. When there is a sudden change in load, the ANFIS controller reaches its steady state value faster and there are no overshoots as compared to the conventional and Fuzzy controller. This proves the robustness of ANFIS controller. The performance has been investigated at different dynamic operating conditions. It is concluded that the proposed ANFIS has shown superior performance and faster transient response over the conventional and fuzzy controller.

APPENDIX -A
INDUCTION MOTOR PARAMETERS

The following parameters of the induction motor are chosen for the simulation studies:

V = 220	$R_s = 0.435\ \Omega$	$X_m = 26.13\ \Omega$
f = 60 Hz	$R_r = 0.816\ \Omega$	$J = 0.089\ kg/m^2$
HP = 3	$X_{ls} = 0.754\ \Omega$	Speed = 1710 rpm
p = 4	$X_{lr} = 0.754\ \Omega$	•

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