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A Comparative Analysis of Fault prediction and Speed Control of Induction Motor using ANN and ANFIS

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Abstract: Induction motors are the commonly used electrical machines. They are cheaper, rugged and easier to maintain, compared to other alternatives. These are now the preferred choice for industrial purposes.Speed control and fault prediction of motor is an important task in the Industrial applications. Various conventional control methods like PI, PID controllers are used for the speed control of Induction Motors. The present scenario is to predict the health and control the speed using Artificial Intelligence techniques such as Artificial Neural Network (ANN), Fuzzy Logic controllers (FLC), Genetic algorithm etc. In this paper is presented a comparative analysis of speed response of Induction motor when both ANN and ANFIS controllers are used. A vector controlled three phase induction motor is modelled. A three phase fault is introduced across the motor terminals. The PI controller is replaced with an ANN controller at first. Then an ANFIS PI model is introduced instead of ANN controller. Simulation result demonstrated that the performance of ANFIS controller is better than that of ANN and PI controller.

Keywords: ANFIS, Artificial Neural Network, Fuzzy PI, Induction Motor.

I. INTRODUCTION

The induction motor is the most common electrical machine that are used as electric drives privileged in the applications of constant speed, due to its advantages, such as low cost, high efficiency, simplicity of design, small inertia, absence of the collector brooms system, and simplicity of design and capability of good self-starting. However, these motors have disadvantages, such as complex, nonlinear, and multivariable of mathematical model of induction motor, and the induction motor is not inherently capable of providing variable speed operation. These limitations can be solved through the use of smart motor controllers and adjustable speed controllers. Since Induction motors are used under various environmental conditions, there are chances to get affect with various faults. Mainly there are two types of faults – Electrical and Mechanical fault. Mechanical faults such as broken rotor bar and bearing fault are more severe than electrical faults. Electrical faults are caused by variation of frequency, unbalance voltage, and inter-turn short circuits. In induction motors the fault can be identified by analysing the speed and the three phase sequence currents. If the speed is negative or greater than reference speed, the motor must be faulty. Also, the motor is healthy only if the three phase currents are balanced and the motor speed is positive.

Vector control is the most common control method that can be used to vary the speed of an induction motor over a wide range. In the vector control scheme, a complex current is synthesised from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor

Commonly, PI controllers are used as the speed controllers in vector control. But tuning of these type of conventional controls is very difficult. This can be done by intelligent controllers. Here an artificial neural network model can be used to replace the PI controller. ANN works on the basis of biological nervous system. It has the ability to learn how to do tasks based on the data given for training or initial experience. A Multi-layer back propagation neural network is trained offline with some priori knowledge that can produce speed command according to the error in speed. Other most common method to control these type of no-linear system is fuzzy logic control. It deals with vagueness and membership function with values between 0 and 1. Adaptive Neuro -fuzzy systems can be used to optimize fuzzy systems' parameters through a learning algorithm and a set of inputs and outputs. The main objective of this paper is to have a comparison between ANN based speed controller and an ANFIS – PI based speed controller. Both the controllers are modelled and performance of both techniques is compared.

II. DYNAMICS OF INDUCTION MOTOR

In industries, induction motors are broadly in the electric drive applications. One of the most implemented control method here is the vector control method which consists of

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control of machines by means of decoupled control of the rotor flux magnitude and the torque-producing current. One issue related to vector control implementation is the difficulty to obtain accurate induction motor model, owing to the variation of motor parameters. A Squirrel cage Induction Motor using the Direct axis and Quadrature axis (d-q) theory is modelled.

A. Electrical system of Induction Motor

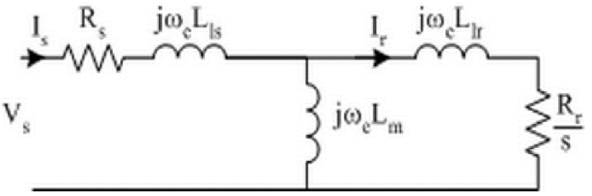

Fig.1. Equivalent circuit model

The parameters in the right part of the circuit are the rotor parameters that have been referred to the stator through the ideal transformer in the machine model. The dynamic equations of the induction motor can be described from the flux equation of the stator phase as, bs and cs (see Fig. 3) and the spatial vector of the stator flux, which is defined as,

$$\bar{\lambda}_s = \lambda_{as} + a\lambda_{bs} + a^2\lambda_{cs} \quad (1)$$

The right part of the equation (1) represents the contribution of each phase. Spatial vector of rotor flux is represented as

$$\bar{\lambda}_r = \lambda_{ar} + a\lambda_{br} + a^2\lambda_{cr} \quad (2)$$

Equations (1) and (2) represent the net stator and rotor flux in the reference frame. The stator and rotor flux are decomposed to orthogonal components as follows:

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_S & L_{SR} \\ L^T{}_{SR} & L_R \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \quad (3)$$

And the impedances are represented as:

$$L_S = L_{LS} + L_C \quad (4)$$
$$L_R = L_{LR} + L_C$$

Where L_S is the stator winding impedance and L_R is the rotor winding impedance. L_{SR} and L_{LS} are Leakage impedances defined as:

$$L_{LS} = \frac{X_{LS}}{W_e} \quad (5)$$
$$L_{LR} = \frac{X_{LR}}{W_e}$$

In the equation (3) the impedance L_{SR} is referred to the common impedance L_c among the stator and rotor, it is defined as:

$$L_{SR} = \begin{bmatrix} L_C\cos(\theta_r) & L_C\cos(\theta_r + \frac{2\pi}{3}) & L_C\cos(\theta_r - \frac{2\pi}{3}) \\ L_C\cos(\theta_r - \frac{2\pi}{3}) & L_C\cos(\theta_r) & L_C\cos(\theta_r + \frac{2\pi}{3}) \\ L_C\cos(\theta_r + \frac{2\pi}{3}) & L_C\cos(\theta_r - \frac{2\pi}{3}) & L_C\cos(\theta_r) \end{bmatrix} \quad (6)$$

In order to define the stator and rotor flux in an orthogonal coordinates, it is used Park's transform as follows:

$$\begin{bmatrix} \lambda_d \\ \lambda_q \\ \lambda_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \quad (7)$$

The matrix equations for the stator and rotor in orthogonal coordinates are

$$\lambda_{dqos} = T_S \lambda_{abcs} \quad (8)$$
$$\lambda_{dqor} = T_R \lambda_{abcs} \quad (9)$$

In the equations (8) and (9) the variables T_S and T_R represent the transformation matrix (e.g.Park's transform) for the stator and rotor respectively.

In order to obtain the simulation equations the following step is to define the stator voltage in the new orthogonal frame. That is:

$$v_{dqos} = T_S v_{abcs} = T_S R i_{abcs} + T_S \frac{d}{dt}\lambda_{abcs}$$
$$= T_S R T_S^{-1} i_{dqos} + T_S \frac{d}{dt} T_S^{-1} \lambda_{dqos} \quad (10)$$
$$= R i_{dqos} + T_S \frac{d}{dt} T_S^{-1} \lambda_{dqos}$$

Now, using the differentiation product rules is defined the stator and rotor voltages, so finally we have:

$$v_{dqos} = R i_{dqos} + \frac{d}{dt}\lambda_{dqos} + \left[T_S \frac{d}{dt} T_S^{-1} \right] \lambda_{dqos}$$
$$= R i_{dqos} + \frac{d}{dt}\lambda_{dqos} + \begin{bmatrix} 0 & -\frac{d\theta}{dt} & 0 \\ \frac{d\theta}{dt} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_{dqos} \quad (11)$$
$$= R i_{dqos} + \frac{d}{dt}\lambda_{dqos} + \begin{bmatrix} 0 & -w & 0 \\ w & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_{dqos}$$

For the rotor the equation is:

$$v_{dqor} = R i_{dqor} + \frac{d}{dt}\lambda_{dqor} + \begin{bmatrix} 0 & -(w - w_r) & 0 \\ (w - w_r) & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_{dqor} \quad (12)$$

Synthesising the equation, we get:

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• Stator

Each component (d, q and o) is defined:

$$v_{ds} = R_S i_{ds} - w\lambda_{qs} + \frac{d}{dt}\lambda_{ds}$$
$$v_{qs} = R_S i_{qs} + w\lambda_{ds} + \frac{d}{dt}\lambda_{qs} \quad (13)$$
$$v_{os} = r_s i_{os} + \frac{d}{dt}\lambda_{os}$$

• Rotor

Each component (d, q and o) is defined:

$$v_{dr} = R_r i_{dr} - (w - w_r)\lambda_{qr} + \frac{d}{dt}\lambda_{dr}$$
$$v_{qr} = R_r i_{qr} + (w - w_r)\lambda_{dr} + \frac{d}{dt}\lambda_{qr} \quad (14)$$
$$v_{os} = r_r i_{or} + \frac{d}{dt}\lambda_{or}$$

The set of equations 13-14 shows voltage and fluxes of stator and rotor in a unified reference frames. Therefore, it is multiplied those equations by the vector $e^{i\theta t}$ obtaining the motor model in a stator frame.

$$v_{ds} = R_S i_{ds} + \frac{d}{dt}\lambda_{ds} \quad (15)$$

$$v_{qs} = R_S i_{qs} + \frac{d}{dt}\lambda_{qs} \quad (16)$$

$$v_{dr} = R_r i_{dr} - w_r\lambda_{qr} + \frac{d}{dt}\lambda_{dr} \quad (17)$$

$$v_{qr} = R_r i_{qr} + w_r\lambda_{dr} + \frac{d}{dt}\lambda_{qr} \quad (18)$$

The mechanical system of equation is defined as:

$$\tau_m = \frac{3}{2}(p/2)(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (19)$$

The electrical rotor speed is defined as:

$$\frac{dw_r}{dt} = \frac{(\tau_m - \tau_L)}{J} \quad (20)$$

The equation 15 to 18 represents stator and rotor voltage components and equations 19 and 20 represent the electromagnetic torque and rotor speed. The modelling of induction motor is completed.

III. PI CONTROLLER

The PI controller computes the controlled output by calculating the proportional and integral errors and summing these two components to compute the output.

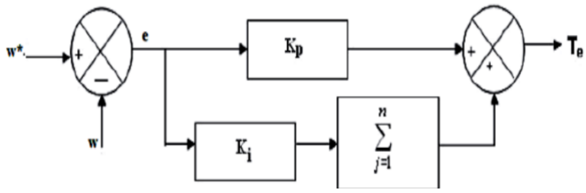

Fig. 2 PI Controller block diagram

The input to the speed controller is the speed error signal, which is difference between the reference speed and actual speed. Command Torque is the output signal of controller where Kp is the proportional gain and Ki is the integral gain.

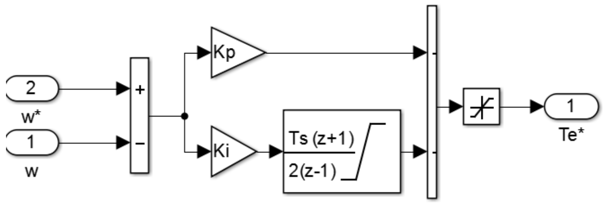

Fig .3 PI Speed Controller subsystems

PI Controller, which is the most commonly used speed controller is designed as a subsystem in the Vector controlled Induction motor with subsystem producing torque command as shown in figure 3.

IV. ANN SPEED CONTROLLER

Neural network is a powerful data modelling tool that is able to capture and represent complex input/output relationships. It's an information processing system that is non-algorithmic, non-digital, and intensely parallel. It consists of a number of very simple and highly interconnected processors called neurons, or like their biological pattern, neural cells in the brain, neurons. The neurons are Connected by a large number of weighted links, over which signal can pass.ANN is an information processing paradigm that is inspired by the way biological nervous systems like the human brain the ANN can be trained to solve the lost complex non-linear problems. There are several applications of ANN in AC drives such as speed control orenergy saver, adaptive speed control, and current control.

Generally, the back propagation method is used for adjusting the neural network weights during the training phase. The basic back-propagation algorithm consists of three steps. The input pattern is presented to the input layer of the network. These inputs are propagated through the network until they reach the output units. This forward pass produces the actual or predicted output pattern.

The two layer feed forward structure of NN model is used in this paper .The tan-sigmoidal function and a pure linear function are used for hidden layers. The two inputs of NN model is firstly feed to the layer of tan sigmoidal function and output of this layer is broadcast to the layer of linear neurons...

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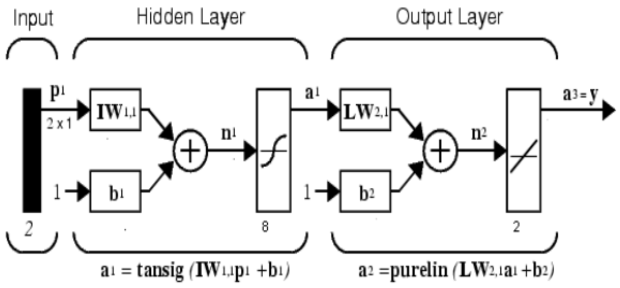

Fig. 4 Neural network model

V. ANFIS BASED SPEED CONTROLLER

ANFIS is basically a graphical network representation of Sugeno-type fuzzy systems endowed with the neural learning capabilities. The network is comprised of nodes with specific functions collected in layers. ANFIS is able to construct a network realization of IF / THEN rules.

A. Fuzzy Logic Controller
Fuzzy Logic control (FLC) has proven effective for complex, non-linear and imprecisely defined processes for which standard model based control techniques are impractical or impossible. The complete block diagram of the fuzzy logic controller is shown and the function of each block and its realization is explained below.

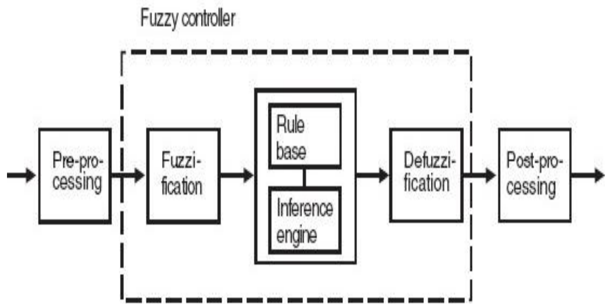

Fig 5 Generalised Fuzzy block diagram

a) Configuration of FLC:
It comprises of four principal components:
- A fuzzification interface
- A knowledge base
- A decision-making logic and
- A defuzzification interface.

b) Fuzzification
Fuzzification interface involves the following functions.
• Measures the values of input variable.
• Performs the function of fuzzification thatconverts input data into suitable linguistic values

c) Knowledge base
Knowledge base consist data base and a linguistic control rule base.

- The database provides necessary definitions, which are used to define linguistic control rules.
- The rule base characterized the control goals and control policy of the domain experts by means of a set of linguistic control rules.

d) Decision making
The decision-making logic is the kernel of an FLC. It has the capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

e) Defuzzication
Defuzzification interface performs the following functions.

- A scale mapping, this converts the range of values of output variables into corresponding universe of discourse.
- Defuzzification, which yields a non-fuzzy control action from an inferred fuzzy control action.

f) Rules creation and inference:
- Expert experience and control engineering knowledge.
- Operator's control actions.
- Learning from the training examples.

In this thesis the fuzzy rules are derived by learning from the training examples.

Rule base for speed control of Induction Motor
The design of a Fuzzy Logic Controller requires the choice of Membership Functions. The membership functions should be chosen such that they cover the whole universe of discourse. It should be taken care that the membership functions overlap each other. This is done in order to avoid any kind of discontinuity with respect to the minor changes in the inputs. To achieve finer control, the membership functions near the zero region should be made narrow. Wider membership functions away from the zero region provides faster response to the system.

Hence, the membership functions should be adjusted accordingly. After the appropriate membership functions are chosen, a rule base should be created. It consists of a number of Fuzzy If-Then rules that completely define the behaviour of the system. These rules very much resemble the human thought process, thereby providing artificial intelligence to the system.[10]

In this paper, the speed controller make use of 49 rules mentioned in the matrix below, based on which Fuzzy Logic controller operates to give the desired result. In this paper, the inputs to the FLC are speed error and derivative of speed error. Error obtained from difference between actual and reference speed.The outputs are Kp and Ki. The rule base matrix for Kp and Kiare shown in table 1 and 2 respectively.

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TABLE I RULE BASE FOR KP

Δkp e \ ec	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
PS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

TABLE II RULE BASE FOR KI

Δki e \ ec	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
PS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

The fuzzy sets are as follows :Z = Zero,NB = Negative Big, NM = Negative Medium, Ns =Negative Small, PS = Positive Small, NB = Negative Big, PB = Positive Big, PM = Positive Medium.

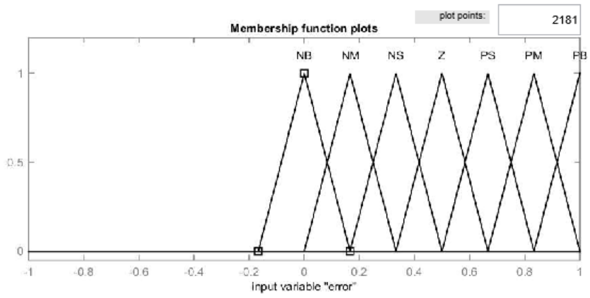

Fig. 6 Membership Function for error

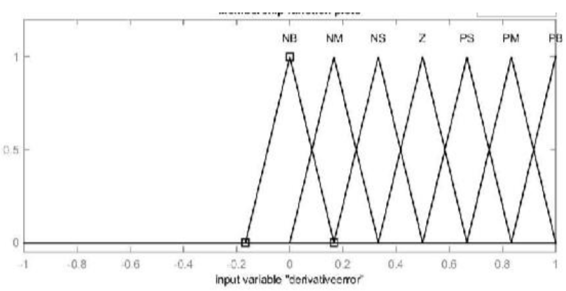

Fig. 7 Membership Function for derivative of error

B. ANFISstructure

ANFIS is a special type of neural network which combines the features of both neural networks and fuzzy logic. ANFIS develops a Takagi -Sugeno fuzzy inference system (FIS) with the help of an input output data set. By using error back propagation algorithm the membership functions of the ANFIS are developed. The inputs to the proposed adaptive Neuro-fuzzy controller are the error (e) and the rate of change of error (de/dt) while the outputs are the proportional gainKp and , the integral gain Ki

The proposed approach has been implemented using Neuro-Fuzzy Designer in MATLAB as shown in Figure 8. The ANFIS model structure is a two input single output feed-forward structure having three hidden layers as shown in Figure 9

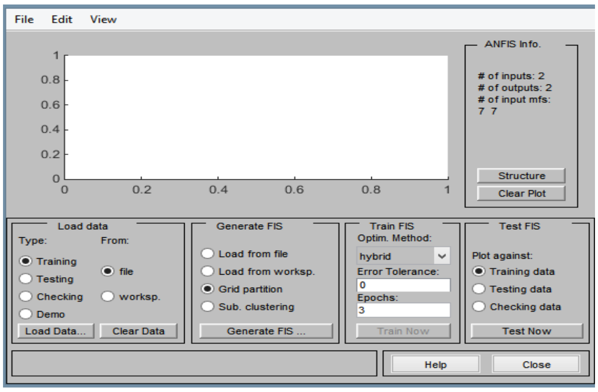

Fig. 8 Neuro-Fuzzy Designer

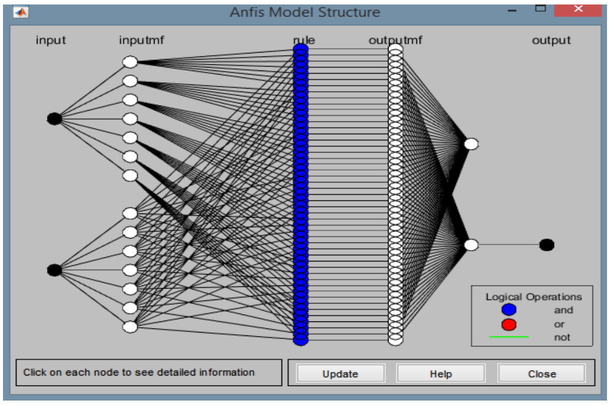

Fig. 9 ANFIS Structure

VI. SIMULATION AND RESULTS

A squirrel cage type induction motor with vector control is modelled. A three –phase fault with switching time with 0.3 to 0.8 seconds is introduced across the motor terminals as shown in figure 10.This is equivalent to an electrical fault` The specification of motor is as shown in Table. III

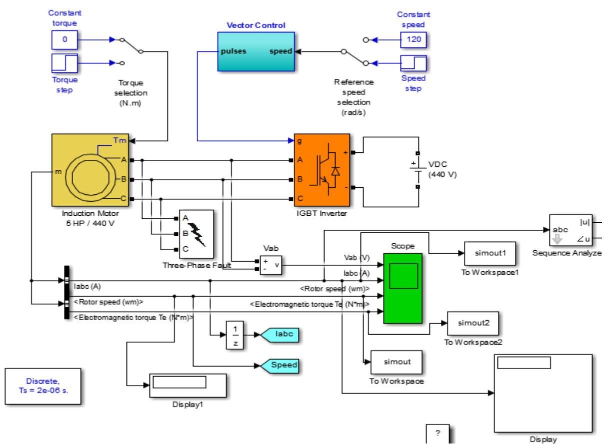

Fig .10 Simulink model of Induction motor with fault

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TABLE.III SPECIFICATION OF INDUCTION MOTOR

Rating of Induction Motor	
4 Pole, Squirrel cage type, 5 Hp , 50Hz, 440v	
Parameters of Induction Motor	
Stator resistance, Rs	0.087 ohm
Stator Inductance, Ls	0.0398 H
Rotor Resistance, Rr	0.228 ohm
Magnetizing Inductance, Lm	1.729 H
Rotor inductance, Lr	0.451H
Moment of Inertia, J	1.662 kg.m^2

A Feed forward neural network is modeled so as to replace the conventional PI Speed controller.The input – target pair is fed and n77K;Lew neural network is formed using "NNTOOL" in the MATLAB Simulink software. NNTOOL method provides the facility to train through one of the methods: Conjugate gradient method and Levenberg-Marquardt method. LevenbergMarquardt method for back propagation is superior to approximate steepest descent method. Hence at first training is carried out using the 'NNTOOL' method. In the neural network TANSIG as transfer function is employed in the hidden layer and PURELIN in the output layer. This Neural network is a three layer model, as shown in figure. 11.

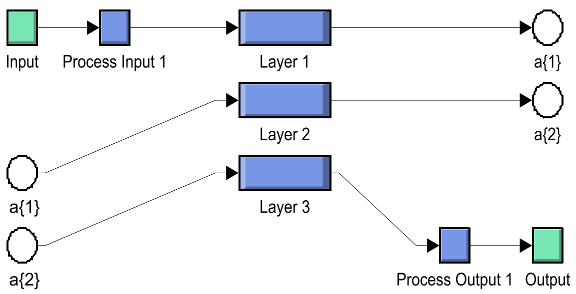

Fig.11 Neural network model

During simulation it was found in display block that the sequence currents was not balanced. This is due to the fault present in the motor. This fault is also can be predicted by analysing the speed and current responses as shown in figure 12 and 13 respectively.

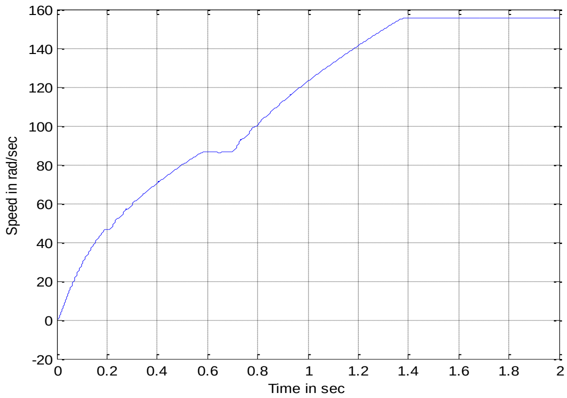

Fig .12Speed response using ANN controller

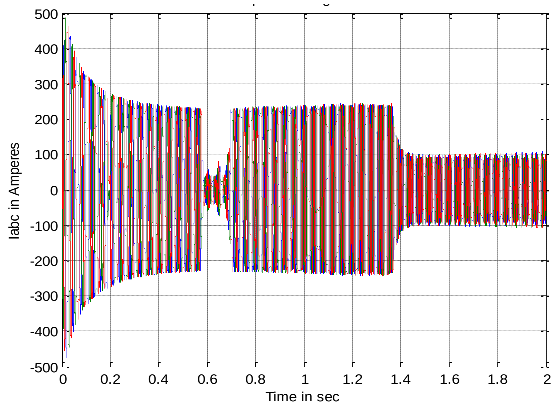

Fig .13Current response using ANN controller

The speed response and current response shows that during fault there is a variation in the speed and current. 0 % overshoot is there in speed response with a settling time of 1.4 sec. Speed settled at 153 rad/sec. ie.maximum speed is not reached.

The next objective was to make an ANFIS model to compensate the variations occurred due to fault which is predicted using the display block and response plots.A Takagi -Sugeno fuzzy inference system (FIS) is developed with help of Fuzzy logic designer . The implementationof ANFIS PI using fuzzy logic controller block in Simulink is as shown in figure 14. The speed response and current response are obtained as in figure 15 and 16 respectively.

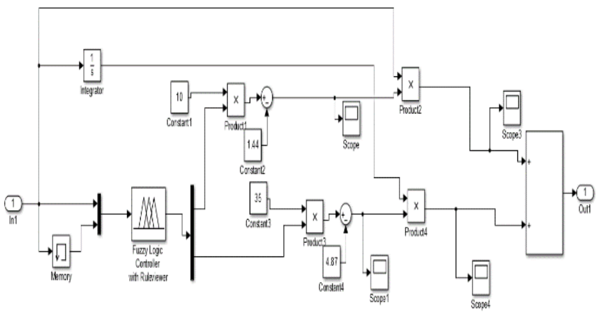

Fig.14 ANFIS PI subsystem implementation

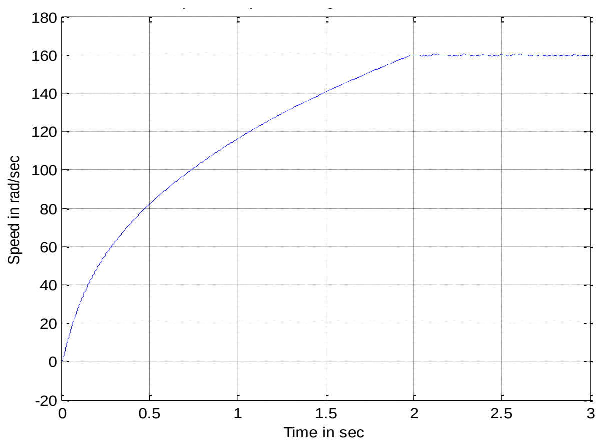

Fig.15 Speed response using ANFIS PI controller

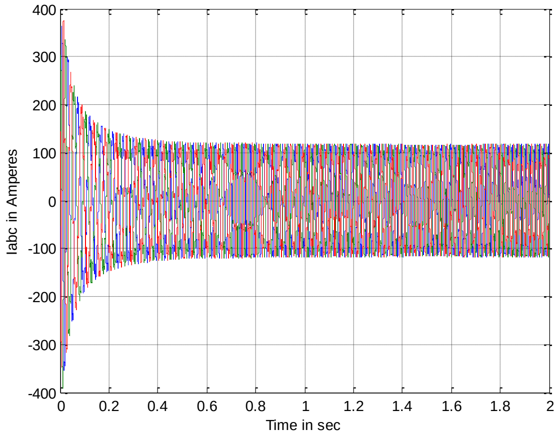

Fig.15 Current response using ANFIS PI controller

From the speed response plot it is clear that the speed change occurred due to the occurrence of fault has been cleared. Settling time found to be 2 sec. Comparison between ANN controller and ANFIS based controller is as shown in table 4.

TABLE IV COMPARISON BETWEEN ANN CONTROLLER AND ANFIS PI CONTROLLER

Controller	Overshoot in %	Rise Time in sec	Settling Time in sec	Steady State error in %
ANN	0	1.25	1.4	2.775
ANFIS PI	0	1.6	2	0.0875

Steady state error is least for ANFIS PI Controller.Also overshoot is nil.But the rise time and settling time is less for ANN controller compared to ANFIS PI.But the steady state error is large . In the case of a control engineer, steady state error requirement should be less than 2 %.Hence ANFIS PI controller is best for considering the Speed Control of Induction Motor.

VII. CONCLUSION

In this paper, the intelligent methods for controlling the speed of an induction motor under fault have been compared. The different methods include artificial neural network and adaptive neuro-fuzzy inference system. The speed and current response plots of both the controllers are analysed.ANN controller has less settling time compared to that of ANFIS controller. But steady state error of ANN controller is high that of ANFIS. In the case of a control engineer , steady state error requirement should be less than 2 %.Hence ANFIS PI controller is best for considering the Speed Control of Induction Motor. Also it can track and attain maximum speed even the motor have any electrical fault.

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