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An Intelligent Adaptive Neuro Fuzzy based Fault Diagnosis System for Severity and Phase Detection of Induction Machine

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Abstract

In this paper, the authors describe a new Adaptive Neuro Fuzzy Inference System (ANFIS) based decision making system developed for stator interturn fault detection of three phase induction machine for both motor and generator mode of operation. This system relies on two state-of-the-art performance index parameters like Sequence Component Amplitude Index (SCAI) and Sequence Component Phase Index (SCPI). A unique Sample Shifting Technique (SST) is utilized to calculate positive and negative sequence components of stator current using its time synchronized samples. SCAI and SCPI are then evaluated based on the magnitude and phase deviation of negative sequence component and these parameters are used to detect fault severity and faulty phase accordingly. The proposed methodology is simulated in MATLAB by modeling a three phase induction machine for both mode with stator inter turn short circuit fault and it is also experimentally verified on a real three phase induction machine.

Key words: Adaptive Neuro Fuzzy Inference System (ANFIS), Performance Index, Sample Shifting Technique (SST), Sequence Component, Inter Turn Short Circuit (ITSC) fault, Three Phase Induction Machine

1. Introduction

Induction machines are very widely used in various industrial processes and plants due to its ruggedness, small price, low maintenance and smooth operation. During operating period, machine faces various kinds of stresses which lead to failure. To avoid unexpected and catastrophic failure, continuous monitoring and fault diagnosis at the early stage is a serious issue to reduce production loss, unscheduled downtime and repair costs [1, 2].

According to the study of IEEE and Electric Power Research Institute, 37% of the Induction motor failure is due to stator inter turn short circuit (ITSC) fault [3]. ITSC fault diagnosis is very difficult to detect at early stage, so to diagnose this fault is a challenging issue. In most of the cases, ITSC fault starts as turn to turn, finally grows as coil to coil, then phase to phase and ultimately causing machine breakdown [2]. An ITSC fault in stator winding leads to an asymmetry between phases, which tend to generate negative sequence component in stator current. The magnitude and phase of current negative sequence component under ITSC fault with balanced supply voltage indicate fault severity as well as fault location [4].

Recently different kinds of soft computing techniques like Expert System, Neural Network, Fuzzy Logic, Adaptive Neuro Fuzzy Inference System, Genetic Algorithm etc. are being adopted for fault diagnostic by correctly interpreting the fault data [5-7]. Among all these methods, ANFIS becomes more popular due to its knowledge extraction feasibility, domain partitioning, rule structuring and modifications. It has mixed capability of machine condition monitoring and fault diagnosis using an inexpensive and reliable procedure like ANN and to provide heuristic reasoning like Fuzzy logic [8]. Using ANFIS algorithm, some works have been done for fault diagnosis of Induction motors and also generators [9-12]. It is evident from these literature surveys that in most of the cases, only faulty phase identification is made and in few cases the severity along with faulty phase is identified. But to detect the severity a lot of complex computation techniques are utilized in frequency domain.

In this proposed work, stator current sequence components of induction machine in normal operating condition and different percentage of stator faults, are studied in time domain. Sequence components are calculated using Sample Shifting Technique, which is explained in section 2. In section 3, detailed description of fault detection methodology with ANFIS system is illustrated. The MATLAB/ Simulink modeling of three phase induction machine along with inter turn fault condition for both motoring and generating mode is explained in section 4. In section 5, hardware experimentation on a 415 V, 50 HZ, 1 HP three phase induction motor is described for verification of fault detection algorithms. Finally, conclusion is drawn in section 6.

2. Sequence component analysis using SST

In this section we briefly explain about the adoption of Sample Shifting Technique (SST) for sequence component evaluation.

Time domain analysis of Sequence components

According to Fortescue's theorem [13], current sequence components of three phase unbalanced system can be calculated as,

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \left[A^{-1}\right] \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad \text{Where, [A]} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \text{ and } \left[A^{-1}\right] = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \qquad (1)$$

The operator $a = 1\angle 120^o$ and $a^2 = 1\angle 240^o$, the subscript (0), subscript (1) & subscripts (2) designates positive, negative and zero sequence components respectively.

W. Lyon substituted these steady state phasors in time-dependent functions modified the concept of Fortescue sequences to the generalized concept of instantaneous sequences [14]. According to Lyon transformation, if $\{W_a(t), W_b(t), W_c(t)\}$ are three phase set of any arbitrary time function, then its symmetrical components can be derived as,

$$\begin{bmatrix} W_0(t) \\ W_+(t) \\ W_-(t) \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \overline{\alpha} & \overline{\alpha}^2 \\ 1 & \overline{\alpha}^2 & \overline{\alpha} \end{bmatrix} \begin{bmatrix} W_a(t) \\ W_b(t) \\ W_c(t) \end{bmatrix} \quad \text{Where, } \overline{\alpha} = e^{j2\pi/3} \qquad (2)$$

But, due to handling with complex number, the complexity of this method will increase when the theorem is applied with some ordinary processor.

Adoption of SST for Sequence component calculation

The above mentioned complexity can be reduced by applying Sample Shifting Technique (SST) algorithm [15] for sequence component evaluation. SST relies upon the fact that a shifted sine wave by any angle can be generated from its original waveform only by rearranging its sample values because shifting of any sinusoidal wave by any angle (or equivalent time) only shifts the time of occurrence of instantaneous amplitudes of the sinusoidal wave by that angle.

For a three phase system, if a particular waveform is considered as A phase and applying the SST corresponding 120^o and 240^o shifted waveforms can be generated only by repositioning the sample values. Similarly for B phase and C phase, the same procedure is repeated to get their corresponding 120^o and 240^o shifted waveform [16].

According to SST, multiplication by operator 'a' on original samples of any phase current, as needed to solve equations (1), is equivalent to 120^o sample shifting and multiplication with 'a^2' is equivalent to 240^o sample shifting from its original wave. So, to evaluate current sequence component in a three phase system using SST, equations (3-4) are utilized with N no. of samples per line cycle.

$$
\begin{aligned}
I_1(n) &= [I_a(n) + I_b(n+N/3) + I_c(n+2N/3)]/3 && \text{for } 1 \le n \le N/3; \\
&= [I_a(n) + I_b(n+N/3) + I_c(n-N/3)]/3 && \text{for } N/3 < n \le 2N/3; \\
&= [I_a(n) + I_b(n-2N/3) + I_c(n-N/3)]/3 && \text{for } 2N/3 < n \le N; \qquad (3)
\end{aligned}
$$

$$
\begin{aligned}
I_2(n) &= [I_a(n) + I_b(n+2N/3) + I_c(n+N/3)]/3 && \text{for } 1 \le n \le N/3; \\
&= [I_a(n) + I_b(n-N/3) + I_c(n+N/3)]/3 && \text{for } N/3 < n \le 2N/3; \\
&= [I_a(n) + I_b(n-N/3) + I_c(n-2N/3)]/3 && \text{for } 2N/3 < n \le N; \qquad (4)
\end{aligned}
$$

3. Formulation of fault detection methodology

In this Section we briefly introduce ITSC fault detection method for induction machine using ANFIS algorithm.

Performance Index parameters

On the basis of the nature of negative sequence component for different fault condition, the fault location and severity are detected by introducing two unique parameters, defined as Sequence Component Amplitude Index (SCAI) and Sequence Component Phase Index (SCPI) [17].

Here $SCAI = (I_1 - I_2)/I_1$, where, I_1 is the magnitude of positive sequence component and I_2 is the magnitude of negative sequence component and $SCPI = (\varphi_1 - \varphi_2)/120$, where, φ_1 is the phase angle of positive sequence component and φ_2 is the phase angle of negative sequence component.

Adaptive Neuro Fuzzy Inference System

The main objective of ANFIS based fault diagnostic system is to learn the relationships between these performance indices with different load conditions (ANFIS inputs) and the corresponding machine condition (ANFIS outputs) which will able to provide machine condition correctly. For training, a suitable data set is prepared by calculating SCAI and SCPI with stator ITSC fault at different phases and different percentages like 2%, 5%, 8%, 10%, 12%, 15%, 18% and 20% under three different loading conditions such as 0 Nm, 10 Nm and 20 Nm. So, for three different loads, total 24 (3 X 8) number of inputs are obtained. Considering three phase fault (24 X 3 = 72) and healthy condition (3), a total 75 training and testing data pattern are generated. During ANFIS training of SCAI and SCPI, out of these 75 data sets, first 3 data set are considered from normal condition and 24 data set for each of the phases A, B, C in sequence, as shown in Fig. 1.

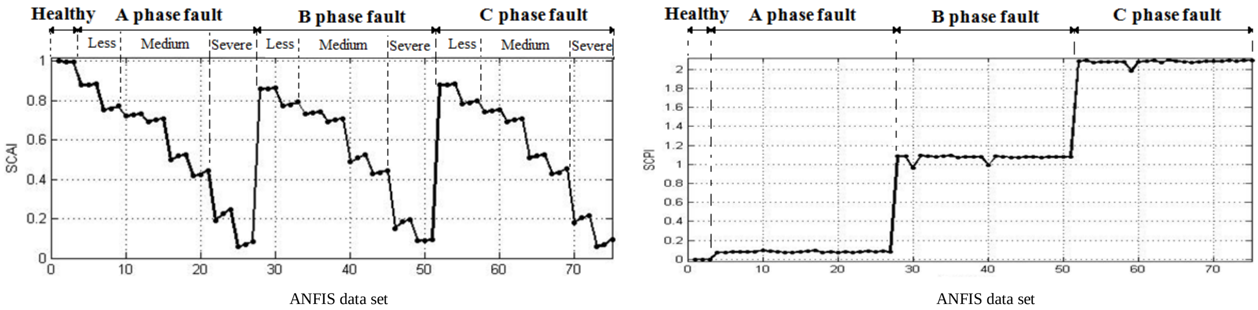

Fig.1. Simulated training input data set

4. Simulation using MATLAB

In the following, we are going to present the mathematical model of induction machine and ANFIS output for both motor and generator mode with ITSC fault condition.

Mathematical modeling of Induction machine

In this paper, the authors develop 3-Φ Squirrel cage Induction machine model in MATLAB/SIMULINK. It is considered that, stator and rotor windings are identical for three phases with equivalent no. of turns and displaced from each other at angle 120°.

Stator and rotor voltage equations of the 3-Φ induction motor can be derived as,

$$V_{abcs} = r_s i_{abcs} + \frac{d}{dt}\psi_{abcs} \tag{5}$$

$$V_{abcr} = r_r i_{abcr} + \frac{d}{dt}\psi_{abcr} \qquad (V_{abcr} = 0, \text{ for Squirrel Cage rotor}) \tag{6}$$

Where, V_{abcs}, V_{abcr} are three phase stator and rotor voltages & I_{abcs}, I_{abcr} are stator and rotor currents, r_s is stator resistance per phase and r_r is rotor resistance per phase.

Flux linkage equations can be expressed as,

$$\begin{bmatrix} \psi_{abcs} \\ \psi_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ L_{sr}^T & L_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \tag{7}$$

Here, stator winding inductance matrix (L_s), rotor winding inductance matrix (L_r) and stator to rotor mutual inductance matrix (L_{sr}) are expressed as,

$$L_s = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \text{ and } \quad Lr = \begin{bmatrix} L_{lr} + L_{mr} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{lr} + L_{mr} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{lr} + L_{mr} \end{bmatrix}$$

where, L_{ls}, Llr, L_{ms}, L_{mr} are stator and rotor leakage and magnetizing inductance.

Considering, electrical angular velocity ω_r and displacement θ_r,

$$Lsr(\theta_r) = \begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r \end{bmatrix} \tag{8}$$

The electromagnetic torque developed by a three phase Induction machine,

$$T_{em} = [i_{abcs}]^T \left[\frac{dL_{sr}}{d\theta_r} \right] [i_{abcr}] \tag{9}$$

Finally, the dynamic torque equation for speed calculation is given below,

$$T_{em} = J \frac{d\omega_r}{dt} + B\omega_r + T_L \tag{10}$$

Where, J is the rotor inertia, ω_r is rotor angular speed in rad/sec, B is the friction coefficient and T_L is the load torque.

Motoring operation with stator ITSC fault

Using equations 5 to 10, dynamic model of a healthy 3-Φ squirrel cage induction motor is developed in MATLAB/ SIMULINK, explained in reference [17]. In this model, stator ITSC is externally created by dividing stator winding associated with fault in two series parts. If, N_s is total no. of stator turns per phase, then $N_s = N_{us} + N_{sh}$, where N_{sh} is no. of shorted turns & N_{us} is no of unshorted turns. So, % of fault can be calculated as (N_{sh}/N_s) x 100%.

Training data set of two input parameters (SCAI and SCPI) is applied to fault detector for gaining optimized architecture to detect ITSC fault of an induction motor. Here, up to 5% fault is termed as ‘less damaged’, 5% to 15% is termed as ‘medium damaged’ and above 15% is termed as ‘severe damaged’ condition. Due to space limitation, some results are given indicating target and actual output. Fig. 2 and Fig. 3 show the ANFIS output for ITSC fault for ‘medium damaged’ in A phase and ‘severe damaged’ in C phase. It is cleared from Fig. 2, output become one for data set ranging from 10 to 21, otherwise zero. It indicates, 5% to 15% damaged ITSC fault in A phase, which treated as ‘medium damaged’. Similarly, in Fig. 3, for 70 to 75 data range output become one, otherwise zero, which indicates above 15% damaged ITSC fault in C phase and treated as ‘severe damaged’ fault.

Generating operation with stator ITSC fault

In this mathematical model, generating mode is obtained by increasing the speed above synchronous speed after its motoring mode of starting. ITSC fault is created in the same way as mentioned above.

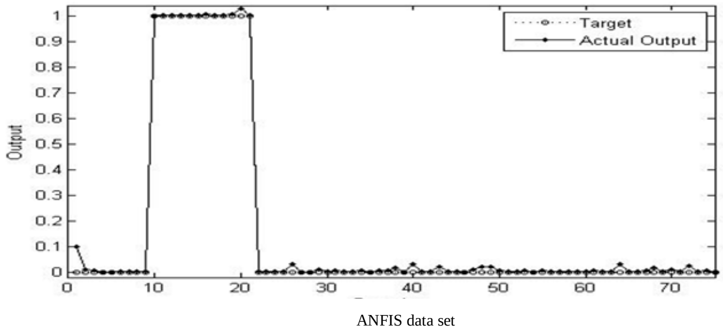

Fig.2. ANFIS output for Stator A phase winding ITSC fault with medium damaged condition

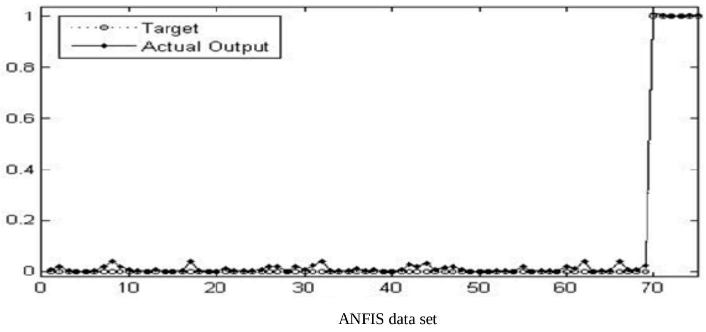

Fig.3. ANFIS output for Stator C phase winding ITSC fault with severe damaged condition

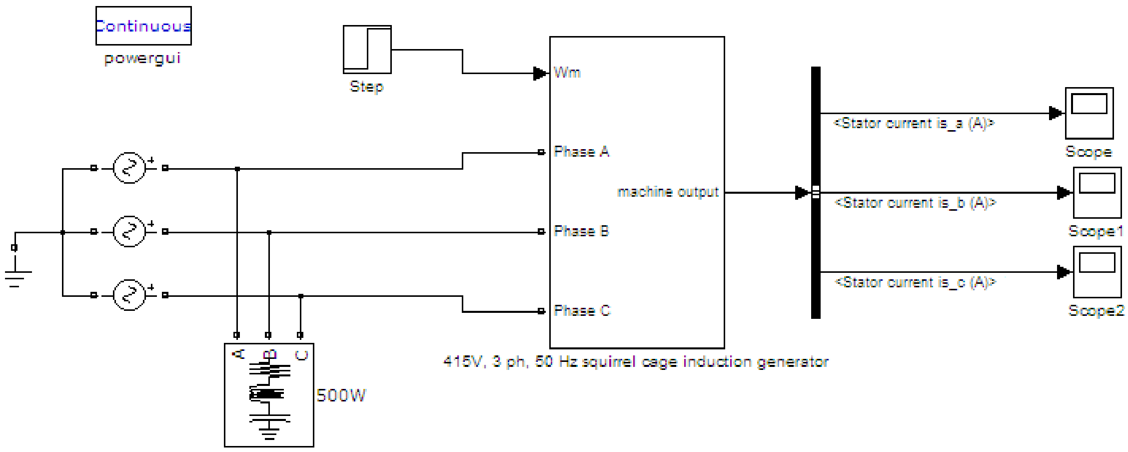

Fig.4. MATLAB/ SIMULINK model of Induction Generator

Then all the case studies are done during generating operation and SCAI, SCPI are calculated. Two ANFIS output for generating mode of operation is given in Fig. 5, 6.

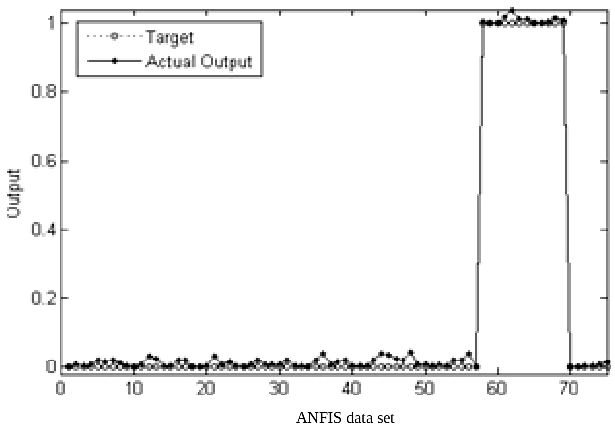

Fig.5. ANFIS output for Stator C phase winding ITSC fault with medium damaged condition

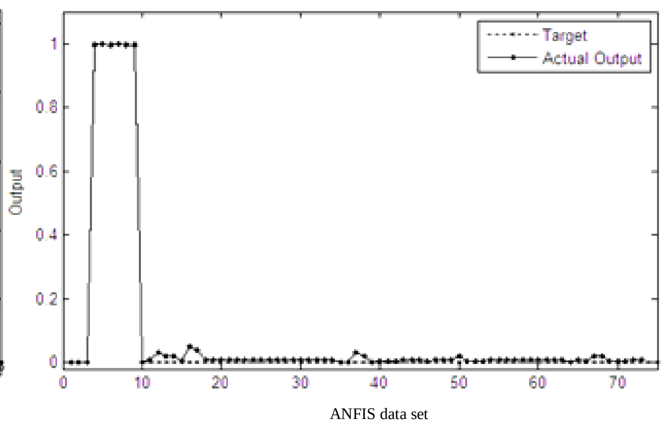

Fig.6. ANFIS output for Stator A phase winding ITSC fault with less damaged condition

5. Experimental Verification

To validate the proposed fault classification approach, a case-study on a 3-phase, 415 V, 1 HP, 50-Hz Squirrel cage induction machine is performed. This motor is tested under healthy and

5% to 20% stator ITSC fault conditions. The three phase stator current samples are collected simultaneously using hall sensors and are stored in PC. The SST is applied to calculate positive and negative sequence components for every current cycle. SCAI and SCPI are then evaluated using these sequence components and are treated as ANFIS input. The detailed diagram of hardware setup is given in Fig. 7. And two test results are illustrated in Fig. 8 and 9.

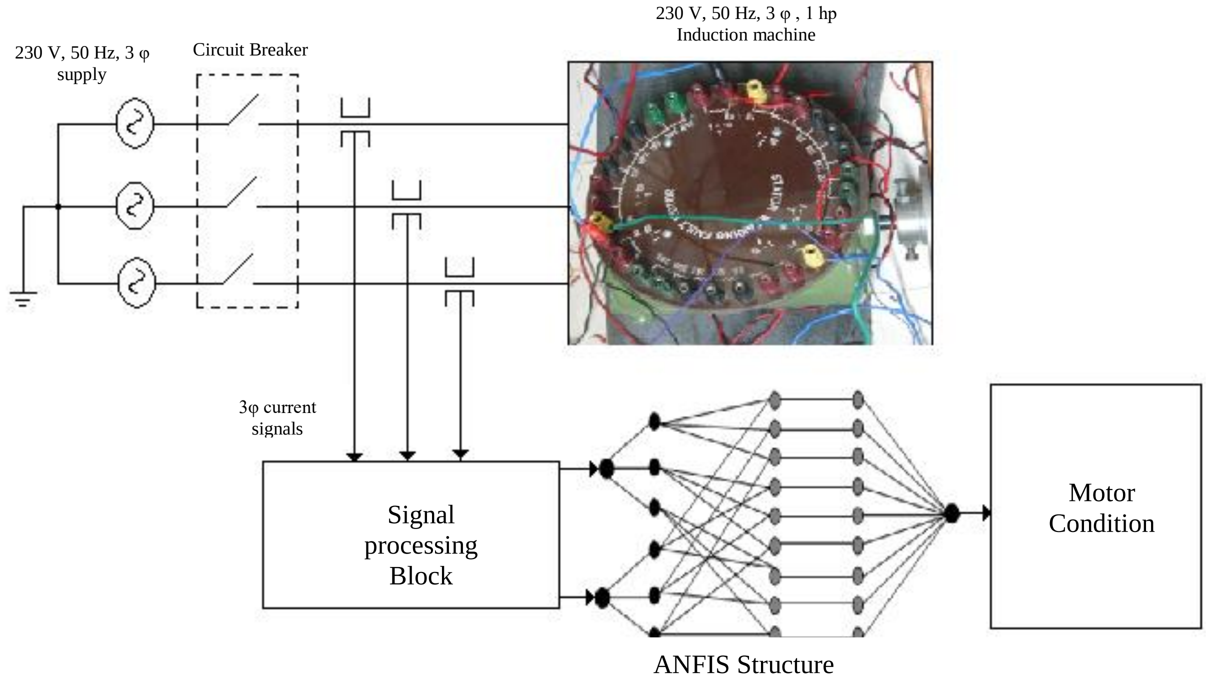

Fig.7. Diagram of hardware setup

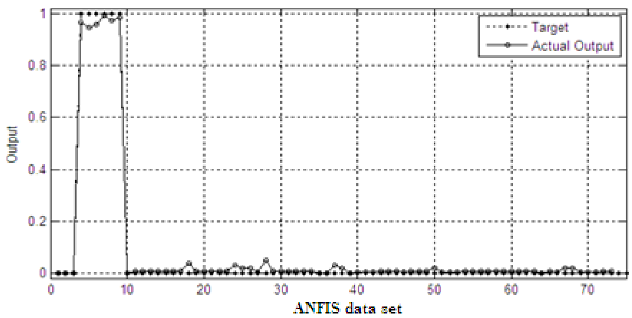

Fig.8. ANFIS output for Stator A phase winding ITSC fault with less damaged condition

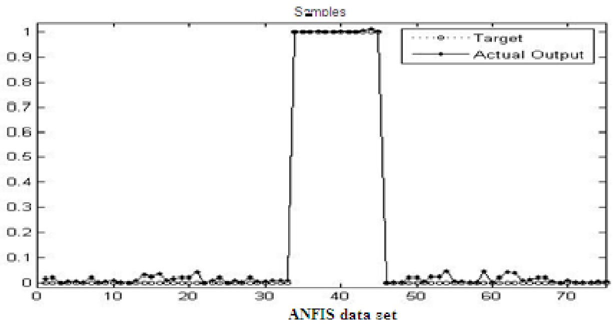

Fig.9. ANFIS output for Stator B phase winding ITSC fault with medium damaged condition

It can be observed from hardware case study, ANFIS output for different fault condition are very much similar with the software result, which proves the accuracy of proposed fault detection method. Due to space limitation, only two test results are shown. But for all other ITSC fault conditions, ANFIS based fault detection system indicates its accuracy.

5. Conclusions

In this paper, ANFIS based ITSC fault detection of three phase induction machine is proposed. The main advantage of this work is only three phase current samples are required. From current samples, sequence components are calculated by Sample Shifting Technique which mainly uses for fault detection. Using SST, sequence components are evaluated by only repositioning current sample values. So, it is very simple method and can be implemented by using an ordinary microcontroller and protection cost can be reduced.

Sequence current components are not so much affected by the quality of power supply as it is calculated using Sample Shifting Technique. The main purpose of using the Neuro-Fuzzy approach is to bring automation in fault diagnosis system with the training of Performance Index parameters (SCAI, SCPI) based on some Fuzzy based rule set. Once the system is trained for specific data over a wide range, it can be applicable to similar types of motor used in plants, and thus there is no need to train the model for each motor. So, proposed diagnosis method can be applied to any type of small and high power induction machines.

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