Rotor Bar Damage Detection in Induction Motor using Haar Wavelet Transforms and Neural Networks

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Abstract— This paper proposes a Haar wavelet combined with Back Propagation Neural Networks (BPNN) method for Rotor damage diagnosis in induction motors. The starting process of an induction motor produces stator currents that are many times greater than the steady state current of the induction motor. For a motor with a damaged rotor bar, the nature of this transient current will be different compared to normal motor. In this work the stator current of normal and damaged motor are transformed using Haar wavelet transform and higher order statistical features such as Energy , Kurtosis Variance and Skewness are estimated in the transform domain and given to a trained BPNN. The BPNN output classifies the stator current to either belong to normal or faulty motor. The performance of the BPPN is computed using confusion matrix parameters and gives high accuracy.

Keywords *–Induction motor, rotor faults, motor current signature analysis, Back Propagation Neural Network, Mean ,Variance, Skewness, Kurtosis, Confusion Matrix*

I. INTRODUCTION

Electric motors are the work horses of the industrialised modern world. There are several million induction motors in operation worldwide at any time. Small electric motors from power outputs ranging from a few watts to large motors that develop megawatts of power are now available and enable mankind to undertake many difficult tasks. The history of electric motors dates back to the early nineteenth century. Many great men, including Franklin, Ampere and Faraday, contributed to the technical developments that culminated in US inventor Thomas Davenport's patenting of the first DC motor in 1837[1]. Induction motors are widely used for many tasks in many industrial processes. More than 30% of electricity produced is consumed by induction motors. Induction motors are well known for their low cost, reliability and long useful life. Induction motor's performance is therefore an important topic for an industrialized society.

Induction motors are constant speed motors. AC Drives enable induction motors to run at varying speeds. Induction motors may develop fault due to improper operating conditions or environmental factors like high levels of corrosive gases in the operating environment [4][9]. The timely detection of faults can prevent permanent damage to motors .This can save money and resources spent on costly repairs[10].

Rotor bar damage originates from electrical, mechanical, thermal or environmental stress.

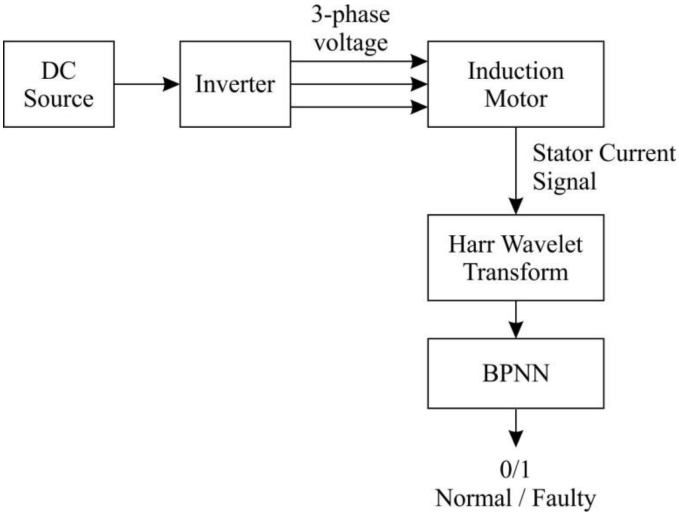

Fig.1 Structure of Fault Detection System

In an induction motor with a squirrel cage rotor the rotor bars are shorted by circular conducting structures called end rings. Rotor bar resistance sharply increase when a rotor bar is broken[7][11] The expression for the rotor phase resistance is

$$R_r = \frac{3R_{bar}}{N_b}$$

where R_{bar} is the resistance of each rotor bar, and N_b is the total number of bars in the rotor structure.

The expression for the resistance of a broken rotor resistance is given by

$$R_r = \frac{3R_{bar}}{N_b - n}$$

where n is the number of broken rotor bar.

The change in resistance is

$$\Delta R = R_{br} - R_r = \left(\frac{1}{n_i} - 1\right) R_r$$

where $n_i = (N_b - n)$,

Signal processing methods which are used to detect electric motor failures, including rotor bar damage in induction motors, are collectively referred to as motor current signature analysis methods. (MCSA).

II. WAVELETS

Wavelet analysis is a method of analysing a signal at different frequency bands at different resolutions. Practically a wavelet analysis on signals can be carried out through wavelet transforms. Fourier transform and its variants analyses signals over a long period of time Short time Fourier transform can deal with a signal of limited duration[7]. The mathematical structure of wavelet analysis is suitable for analyzing short -term transients. The starting process of an induction motor produces short duration transient stator current of high magnitude.

A wavelet is a function. Normally a basic wavelet function is designated by the term $\psi(t)$ .Wavelets can be generated by scaling and translating the basic wavelet function $\psi(t)$,which is often called as mother wavelet.

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right)$$

where s is called the scale factor and τ is the translation factor. Any function in time do not qualify as a wavelet. For a function to be a wavelet certain conditions are to be satisfied.

First condition is the admissibility condition which states that.

$$\int \frac{|\psi(\omega)|^2}{|\omega|} d\omega < \infty$$

where $\psi(\omega)$ is the Fourier transform of $\psi(t)$

The second condition is $\int \psi(t)\, dt = 0$. The function must be oscillatory and its mean should be zero. In discrete wavelet transform any function $f(t)$ can be represented by dyadic dilation and translation of wavelet function $\psi(t)$ [8]

$$f(t) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} d(k,l)\, \psi(2^{-k} t - l)$$

Any family of orthonormal wavelets can be represented by the LPF coefficients $h(n)$

From the above conditions the high pass filter coefficients can be obtained using the equation

$$g(n) = (-1)^n h(L-1-n).$$

where L is the length of the filter h(n). The filter bank implementation of one stage wavelet transform based on equations can be represented as follows[5].

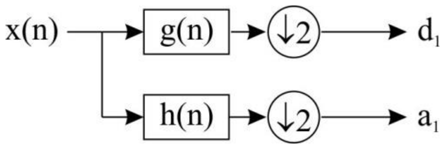

Fig.2 Single Stage Wavelet Transform

In Haar wavelet scaling function $\phi(t)$ is given by [8]

$$\phi(t) = \begin{cases} 1 & 0 \le t < 1 \\ 0 & otherwise \end{cases}$$

The wavelet function $\psi(t)$ is given by

$$\psi(t) = \begin{cases} 1 & 0 \le t < \frac{1}{2} \\ -1 & \frac{1}{2} \le t < 1 \\ 0 & otherwise \end{cases}$$

The corresponding coefficients of the filter h[n] and g[n] are given by

$$h(n) = \left\{\frac{1}{2}, \frac{1}{2}\right\}$$

$$g(n) = \left\{\frac{1}{2}, -\frac{1}{2}\right\}$$

In this work stator currents are transformed using Haar Wavelets. Haar wavelet transform is the simplest wavelet transform. It is not a continuous or differentiable transform. However, its discontinuous nature makes it an appropriate transformation to analyse signals with sudden transitions. [6] . Signals associated with rotor bar failure also fall into this category. In this work a three level wavelet transform is used as shown in figure, d_1,d_2,d_3 represents detail coefficients in each level while a_1 represents approximation coefficient.

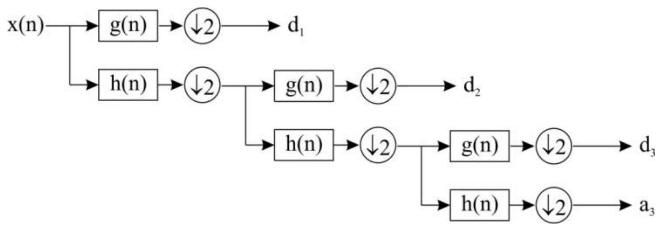

Fig.3 Three Stage Wavelet Transform

III. BACK PROPAGATION NEURAL NETWORK

Artificial neural networks mimic the working of neural structure of living beings. In biological neural networks neurons are interconnected by a network of connections. In artificial neural networks too, the same general principle is used. The most remarkable feature of neural network lies in its ability to learn by means of adapting its activation function in order to match the input and output patterns. The interpolating capability of the neural network is used for getting output for unseen input patterns. Artificial neural networks are specified by their network structure, node characteristics, and their training rules. The fundamental components of artificial neural network are nodes (neurons) and weights (interconnections). The nodes accept weighted sum of outputs from previous nodes and produces an output which depends on activation function[2].

A neural network based on the principle of back propagation has three layers of neurons. An input layer, hidden layer and an output layer. The Fig xx shows a 3 layer BPNN. The BPPN maps an input pattern X=(x_1,x_2, x_N) to output pattern Y= (y_1,y_2, y_M). The neural network has to be trained using a training data set. For this a database consists of known input ,known output pattern pairs (X,Y) are used. The three layer BPNN is represented by input to hidden layer weights, V_{ij} and the hidden layer to output weight, W_{jk}

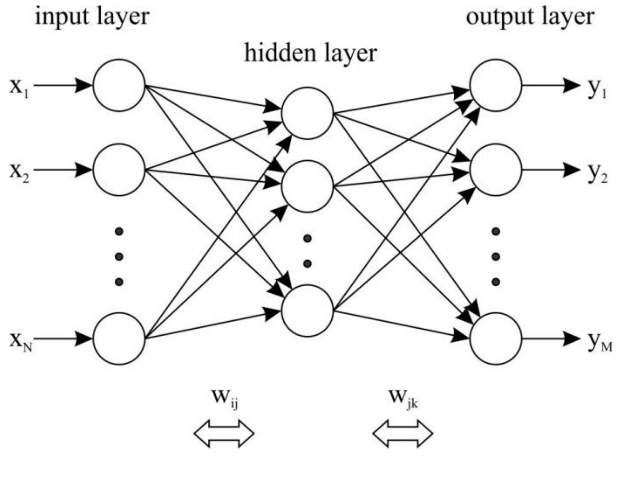

Fig.4 A Back Propagation Neural Network

In BPNN each neuron accepts weighted sum of inputs from previous layer out and produces an output by using the activation function f(.). The examples of activation functions are sigmoid and tanh functions. The input to hidden later weights and hidden layer to output layer are represented by V_{ij} and W_{jk}. The error E between the computed output y_k to the target output t_k for input pattern Xi. This is done by updating the weights V_{ij} and W_{jk} by following equations of ΔV_{ij} and ΔW_{ij}

$$W_{jk} = W_{jk} + \Delta W_{jk}$$

$$\Delta W_{jk} = -\alpha \frac{\partial E}{\partial w_{jk}} + \beta\Delta^{*} W_{jk}$$

$$V_{ij=} V_{ij} + \Delta V_{ij}$$

$$\Delta V_{ij} = -\alpha \frac{\partial E}{\partial v_{ij}} + \beta\Delta^{*} V_{ij}$$

where * denotes previous change in weight. α is the learning rate and β is the momentum factor. The above equations are implemented using standard BPNN training algorithm. The momentum factor increases the speed of convergence and helps to escape from falling to local minimum. Typical value of α is 0.75 and β is 0.15[2][3].

IV. STATISTICAL FEATURES

The dimension of a stator current signal is normally greater than ten thousand, so the wavelet transform length will also be the same. In order to reduce the computational complexity of the neural network dimensionality is required. Second order statistical parameters such as variance, average energy, skewness and kurtosis are the commonly used higher order statistical features. These features capture predominant characteristics of a signal in transform domain and will have different values for normal and faulty stator signals. These parameters are calculated using following equations.

A. Average Energy

$$E = \frac{1}{N}\sum_{i=1}^{N} x_i^2$$

B. Variance

Variance is a measure of the tendency of data elements to cluster around some particular value.

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2,$$

$\bar{x}$ is the average value

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

C. Skewness

Skewness is a statistical measure of asymmetry in the probability distribution of a real valued random variable.

$$Skewness = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{x_i - \bar{x}}{\sigma}\right]^3$$, σ is standard deviation

V. SIMULINK MODEL FOR INDUCTION MOTOR SIMULATION

Simulink is a simulation tool available with Matlab. It is an effective tool for simulating electrical, electronic and mechanical systems. Matab programs can be incorporated in to Simulink simulations to execute mathematical operation on the signals originating from the model. A three phase, sine PWM modulated, three level inverter using power MOSFETs as switching elements is used in this model of inverter. The specification used in this model is three phase 50Hz, 5hp motor. Same model with a change of rotor resistance was used to simulate normal and faulty motor. The increase in rotor resistance to simulate rotor faults is set as an increase of 5% increase in rotor resistance Extracted stator currents from the simulations are given in figures.

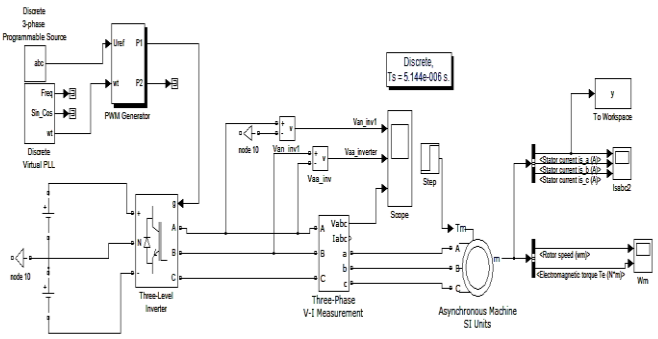

Fig.6 Simulink Model

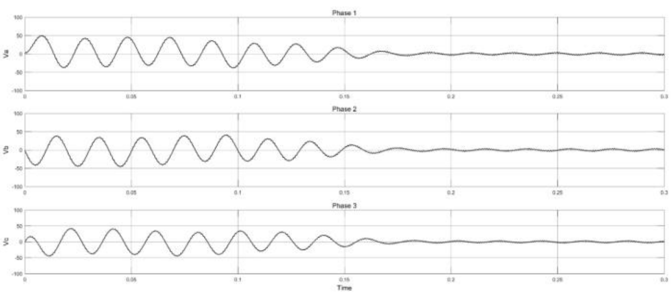

Fig.7 Stator current output from SIMULINK model

VI. METHODOLOGY

Fig.1 shows the proposed methodology. The stator signals are simulated using Simulink model as explained in section V. Initially the BPNN is trained using statistical features of stator current of a normal and faulty motor extracted under different operating conditions. For training the BPNN the database structure is shown below. In this work the number of input dimension is 20 which corresponds to the 5 statistical parameters from each level of wavelet decomposition and number of output neurons is 1 which is 0 for normal motor and 1 for faulty motor.

$$\left.\begin{array}{ll} x_1, x_2, \ldots\ldots x_N & y = 0 \\ x_1, x_2, \ldots\ldots x_N & y = 0 \\ x_1, x_2, \ldots\ldots x_N & y = 0 \end{array}\right\} \Rightarrow Normal$$

$$\left.\begin{array}{ll} x_1, x_2, \ldots\ldots x_N & y = 1 \\ x_1, x_2, \ldots\ldots x_N & y = 1 \\ x_1, x_2, \ldots\ldots x_N & y = 1 \end{array}\right\} \Rightarrow Faulty$$

The trained BPNN can be used for testing the faulty condition of the motor. For this, wavelet transform of the stator current of the motor is computed and higher order statistical features are computed in the transform domain. The trained BPNN accepts input as the statistical features and outputs a value 0 or 1 indicating whether the motor is normal or faulty.

VII. RESULTS

For testing the proposed methodology, the stator signals are simulated using Simulink model for normal and faulty motors under different operating conditions. The computation of statistical features, implementation of Haar wavelet transforms, BPNN training and testing are implemented in Python environment. Pywavelet library is used for implementing wavelet transform and KERAS deep learning library is used for implementing BPNN. For training the BPNN a training dataset which consists of statistical features from stator current of 22 normal and 22 faulty conditions are used. In this work training of neural network converged after 2000 iterations. To test the neural network, a dataset consisting of statistical features from stator current of 44 normal and 44 faulty conditions are used. The test pattern includes the training patterns also. The results are summarized in Confusion Matrix.

Table 1 Confusion Matrix for Harr Wavelet and BPNN

		Actual Class	
		Normal	Faulty
Predicted Class	Normal	44	**1 (FP)**
	Faulty	**0 (FN)**	43 (TN)

The performance evaluation is done based on TP rate, accuracy and

$$TP\ rate = \frac{TP}{TP+FN}$$

$$precision = \frac{TP}{TP+FP}$$

$$accuracy = \frac{TP+TN}{P+N}$$

The computed values are 99%, 98% and 100% which shows the effectiveness of proposed methodology.

VIII. CONCLUSION

This paper presents an approach for rotor fault detection of induction motor using Haar Wavelet and BPNN Classification. The statistical features in transform domain can classify a stator current to be a normal or faulty based on the BPNN output. The confusion Matrix parameters are also indicates that the combination of Haar Wavelet and BPNN is an effective tool in motor current signal analysis.

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