INTER-TURN FAULT DETECTION IN INDUCTION MOTOR USING STATOR CURRENT WAVELET DECOMPOSITION

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ABSTRACT

A new method for the early detection of inter-turn faults in an induction motor is proposed in this paper. Simulation and experimental results shows that the proposed method works perfectly even under the dynamic load conditions of the induction motor. Reference frame transformation theory forms the backbone of the modeling of inter-turn fault of induction motor. The fault model has been prepared based on the synchronous reference frame. Mathematical model thus developed is then simulated using MATLAB/SIMULINK®. Stator current signal were acquired using hall-effect sensor and NI Labview, which is further processed using Matlab software to obtain their wavelet coefficients up to 6th level of decomposition. Statistical features of these wavelet coefficients were then extracted, analysed and it clearly indicates the interquartile range as a feature. A unique characteristic of the interquartile range of the 6th level detailed wavelet coefficient obtained from the stator current is identified as a doable feature for the detection of inter-turn fault. Even the transient changes occurred in the stator current signal can be identified using this method, which is its advantage over the conventional signal processing techniques. A laboratory set up was made with the inter-turn fault intentionally introduced in the stator winding of the induction motor to verify the proposed method. The interquartile range of the 6th level detailed wavelet coefficient of the stator current varies as the fault is developed in the motor, in the case of experimental data as well. It is observed that the results obtained from this experimental setup closely matches with the simulation results, which confirms the compatibility of the feature and correctness of the model.

Keywords: Wavelet Transformation, Statistical parameters, Induction Motor Faults, Inter-turn fault detection, Fault Modeling, Stator Current Transformation, Synchronous reference frame.

I. INTRODUCTION

It is important to detect the fault in induction motors in an early stage itself due to the cut-throat competition and stringent reliability standards. As far as the stationary signals are concerned, conventional signal processing techniques such as FFT analysis, cosine transform etc. were used earlier to analyse the fault condition and are proved to be working perfectly.

Among the total induction motor faults, around 30-40 % are related to the stator winding insulation and core. It can also be seen that a large portion of stator winding-related faults are initiated by insulation failures in several turns of a stator coil within one phase [1]. Among the possible causes, thermal stresses are the main reason for the degradation of the stator winding insulation. Generally, stator winding insulation thermal stresses are categorized into three types: aging, overloading and cycling [2]. The contamination of the insulating materials used in the induction machines, combination of thermal
overloading and cycling, transient voltage stresses, mechanical stresses etc. are the other possible reasons for the deterioration of the insulation. Electrical stresses, mainly related to the machine terminal voltages, also cause insulation degradation. Among the various electrical stresses, partial discharges (PDs) in the windings and transient voltages at the machine terminals are considered as the major contributors.

Broken rotor bars, vibration resulting from unbalance in rotor, air-gap eccentricity, coil movement, loose bearings, worn bearings, etc. are some of the mechanical reasons, accelerating the insulation degradation [2]. With the increased emphasis on energy conservation and high performance motor control, the use of pulse width-modulated voltage source inverters (PWM-VSIs) has grown at an exponential rate. This has made the stator windings open to higher electrical stresses. High speed PWM operations introduce high rate of rise of transient voltages at the machine terminals. Current in the stator winding produces a force on the coils that is proportional to the square of the current. This force is at its maximum under transient overloads, causing the coils to vibrate at twice the synchronous frequency with movement in both the radial and the tangential direction. This movement weakens the integrity of the insulation system [3]. Contaminations due to foreign materials can lead to adverse effects on the stator winding insulation.

Stator winding-related failures can be broadly classified into the following four groups: open-circuit faults, turn-to-turn, line-to-ground, line-to-line, and single or multi-phase winding. Among these four failure modes, turn-to-turn faults (stator turn faults) have been considered as the most challenging one since the other types of failures are usually the consequences of turn faults. It can be seen that among the faults, the inter turn faults are the most difficult fault to detect at an early stage itself. To solve the difficulty in detecting turn faults, several methods have been suggested [3]-[15], [18]. Because of this, remarkable improvements have been achieved in the area of stator turn fault detection. Nevertheless, the question about the delay time between a turn fault and other severe failures still remains to be answered. The internal asymmetry due to inter turn fault will cause the circulation of extremely high currents in the portion of the winding affected by the fault, thus contributing to the degradation of other portions of the windings. The lead time between the start of the fault and the complete failure of the machine depends on several factors, namely the initial number of shorted turns, winding configuration, rated power, rated voltage, environmental condition etc. [4].

If the fault can be predicted at an early stage, a catastrophic effect can be avoided, the machine can be protected as well as the safety of the working personnel shall be ensured. In the case of a stator turn fault, a large circulating current will be produced, leading to excessive heat generation in the shorted turns. The heat, which is proportional to the square of the circulating current, accelerates the severity of the fault to a destructive level [5]. If this fault is not detected at the early stage it will be propagated and will lead to phase to ground or phase-to-phase fault which in turn may lead to the damage of the machine. As the inter turn fault is one of the major reasons for the machine failure, this paper deals with an early and efficient method for its detection using wavelet based technique. Intensive investigations on stator turn faults revealed that the faults introduce specific changes in the electric properties of the machines. This has created a great deal of scope to develop methods for the detection of a turn fault [3]-[15]. In the proposed method, the stator currents are first converted to proportional voltage signals, which is sampled at regular intervals and acquired in a PC using data acquisition card. Wavelet decomposition of these signals were then carried out, which will take care of the time as well as frequency resolution simultaneously, resulting in the flawless capture of aperiodic, dynamic variations in the signals, when the fault is developed.

II. LITERATURE SURVEY

As the induction motors form the major work horse in most of the industries, fault detection of it is always indispensable, as far as the reliability of the system is concerned. Due to this, many of the researchers were attracted towards it and a lot of efforts were put to predict the performance of induction machines, using various modeling or simulation techniques and tools. Fault monitoring techniques of induction motors using stator currents is one among them [10]. For the non stationary conditions of the induction motor, one of the possible fault detection methods is by analyzing the power spectral density in
wavelet decomposition of stator current waveform [4]. The theory of instantaneous symmetrical components is used for the detection of insulation faults in a three-phase induction motor [5], [6]. The loci of positive and negative sequence components of currents overlap each other under healthy winding conditions as their major and minor axes coincide [6]. When an inter-turn short circuit occurs, these axes do not coincide. But this method didn’t consider the dynamic nature of the loading conditions, which is a major disadvantage. A multiple coupled circuit approach is also proposed for the modeling of induction motor, which is then extended for the stator fault condition. The evolution of an inter-turn short-circuit causes a spectral component in the line current having a frequency thrice the supply frequency and an increase in the amplitude of the principal slot harmonics [7].

The star point voltage of an induction motor with wye-connected stator windings shall also be monitored for the stator fault detection [8]. The online current monitoring system that uses both spectrum analysis of machine line current and Extended Park’s Vector Approach techniques for fault detection and diagnosis in the stator and in the rotor is also available [9]. The major limitation of this method is that it does not have inherent ability to discriminate unbalance supply voltage condition and also cannot predict the severity of faults. A simplified mathematical model of the motor in the presence of stator inter-turn short circuit uses the stationary reference frame as well as clockwise and counterclockwise synchronous reference frames [10]. This will allow the extraction and manipulation of the information contained in the motor supply currents in a way that the effects introduced by the fault are easily isolated and measured [8]. The same method is proposed in direct torque controlled (DTC) induction motor drives [7]. The method in [5] suggests that it is possible to acquire the information on online stator winding turn fault by a simple and robust sensor-less technique based on monitoring an off-diagonal term of the sequence component impedance matrix. The major handicap of this method is the difficulty in online computation of the change in negative sequence impedance.

A traditional electrical model of the induction motor is used for predicting the faults of induction motor, where the typical symptom of 100Hz ripple in electromagnetic torque and the speed is employed [11]. In a current monitoring method for the detection of stator turn fault, the stator winding itself is considered as the sensor [12], [23]. A winding-function-based method for modeling poly-phase cage induction motors with inter-turn short circuit in the machine stator winding suggests that no new frequency component will arrive in the current spectra as a consequence of turn fault but some of the existing frequency components dominate under fault conditions [13]. A transient model for an induction machine with stator winding turn faults is derived using reference frame transformation theory [12]. In all these methods of fault detection [3]–[16], conventional and frequency based signal processing techniques were adapted.

In detecting faults on a transmission line [18], another algorithm which uses both entropy and energy of the decomposed signals is suggested. Also, for the fault detection of power system applications such as locating and power quality disturbance classification [19], similar method is suggested. Here the current signals are decomposed and the features are extracted using suitable signal processing methods. A similar method has already been used in biomedical applications like analysis of ECG signals for classifying normal and abnormal functioning of human heart [21]. In the method suggested in this paper, advantages of these techniques are used in the fault detection of induction motor, which uses wavelet transform of stator current to extract the features.

In the existing scenario, it is evident from the literature that the demand for timely and efficient fault detection scheme is becoming more significant. The electrical faults in the machine can be effectively detected by motor current analysis where as mechanical faults such as bearing faults and rotor eccentricity can be determined by vibration analysis. Due to the increased relevance of diagnosis of stator related faults, which stands in the second place among the various faults of induction motor, stator inter turn fault detection has been considered in this paper. A MATLAB/SIMULINK model is developed for the three phase induction motor with stator inter-turn fault, which is used to extract the features that can be used for the fault detection.
III. Stator inter-turn fault modeling

A model of the induction motor in which the rotating frame is the synchronous reference frame, is used in this work for the dynamic modeling of the inter turn fault. In this method the original a-b-c voltage, current and flux linkages are transformed into q-d-0 reference axis so that they can be analyzed as a dc quantity [22], [25]-[27]. Relevant features for the fault detection were identified by analyzing stator current of the healthy motor as well as the faulty motor modeled in the d-q-0 frame.

III.1 Healthy motor modeling equations

Following assumptions were made for the modeling of the motor. Stator windings are sinusoidally distributed, windings are displaced at 120°, stator windings are identical, $N_s$ is the number of turns and $r_s$ is the resistance per phase. For the present case study, the rotor windings are also considered as three identical sinusoidally distributed windings, displaced at 120°, with $N_r$ as equivalent turns and $r_r$ as resistance per phase. The state of operation remains well below the magnetic saturation. The positive direction of magnetic axis of each winding is shown in Fig. 1.

![Fig. 1. 'abc’ and synchronous reference frames.](image)

The voltage equations in machine variables may be expressed as [25]-[27].

\[
\begin{align*}
    v_{abcs} &= r_s j_{abcs} + p \lambda_{abcs} \\
    v_{abcr} &= r_r j_{abcr} + p \lambda_{abcr}
\end{align*}
\]

In the above equations the subscripts ‘s’ and ‘r’ stand for the variables and parameters associated with stator and rotor circuits respectively. Both $r_s$ and $r_r$ are diagonal matrices with equal non zero elements. $v$ and $i$ are the voltage and current, $\lambda$ is the flux linkages and $p$ is the differential operator. For a magnetically linear system, the flux linkages may be expressed as

\[
\begin{bmatrix}
    \lambda_{abcs} \\
    \lambda_{abcr}
\end{bmatrix} =
\begin{bmatrix}
    L_s & L_{sr} \\
    L_{sr}^T & L_r
\end{bmatrix}
\begin{bmatrix}
    i_{abcs} \\
    i_{abcr}
\end{bmatrix}
\]

Since the machine and power system parameters are always given in per unit of a base impedance, it is convenient to express the voltage and flux linkage equations in terms of reactance rather than inductances. The voltage equations written in the expanded form are:
\[
\begin{align*}
\nu_{qs} &= r_s \nu_{qs} + \frac{\omega_s}{\omega_b} \psi_{ds} + \frac{p}{\omega_b} \psi_{qs} \\
\nu_{ds} &= \nu_{ds} + \frac{\omega_s}{\omega_b} \psi_{qs} + \frac{p}{\omega_b} \psi_{ds} \\
\nu_{0s} &= r_s \nu_{0s} + \frac{p}{\omega_b} \psi_{0s} \\
\nu_{qr} &= r_r \nu_{qr} + \frac{\omega_s - \omega_b}{\omega_b} \psi_{\psi} + \frac{p}{\omega_b} \psi_{qr} \\
\nu_{dr} &= r_r \nu_{dr} - \frac{\omega_s - \omega_b}{\omega_b} \psi_{\psi} + \frac{p}{\omega_b} \psi_{dr} \\
\gamma_{0r} &= r_r \nu_{0r} + \frac{p}{\omega_b} \psi_{0r}
\end{align*}
\]

where \( \lambda = \frac{\omega}{\omega_b} \) in which \( \omega_b \) is the base speed.

The expression for electromagnetic torque developed in the machine in terms of synchronous reference frame variables is given as

\[
T_e = \frac{3}{2} \frac{P}{\omega_b} \left( \psi_{ds} \nu_{qs} - \psi_{qs} \nu_{ds} \right)
\]

where \( P \) is the number of poles of the machine.

The mechanical equation of the machine is given by

\[
T_e = 2H \frac{d}{dt} \left( \frac{\omega_b}{\omega_b} \right) + T_L + T_f
\]

where \( H \) is the inertia constant, \( T_L \) is the load torque and \( T_f \) is the frictional torque of the machine.

\[
H = \left( \frac{1}{2} \right) \left( \frac{2}{P} \right)^2 J \omega_b^2 \frac{P_b}{P}
\]

where \( P_b \) is the base power of the machine.

Equations (1) to (12) represents the dynamic model of a healthy induction motor, which were used to simulate in MATLAB/SIMULINK. In the next section, extension of this model, for taking care of the stator inter-turn fault condition is discussed.

### III.2 Modeling the inter-turn fault

The mathematical model developed in the q-d-o reference frame is used for the prediction of inter-turn fault in the induction machine. When an inter-turn short circuit arises, as per the proposed model, the faulty phase is split into two sub windings located along the same magnetic axis. As a result of this, four voltage equations can be written for the stator windings. The assumption made in the simplified model is that the distribution of leakage inductance between the two stator sub windings, originated by the development of the short circuit, is directly proportional to the square of the number of turns shortcircuited.

The six voltage equations representing the three stator and three rotor windings of the motor shall now be obtained by merging the two equations related to the winding affected by the fault into just one equation. In addition
to this, a voltage equation related to the loop containing the fault is also developed to represent the faulty motor completely.

All the stator and rotor voltages are then transformed to q-d-0 reference frame and compared with the equations of healthy machine. Also, the equations for the overall model can be written as the sum of normal supply voltages and the voltage due to the contribution by the fault. Equations (13) to (25) represents the final voltage equations for the stator and rotor windings, as well as the short-circuit current and the electromagnetic torque developed by the motor.

\[ v_{qs} + \Delta v_{qs} = r_{s} i_{qs} + \frac{\partial \psi_{qs}}{\partial \theta_{s}} + \frac{p}{\partial \theta_{s}} \psi_{qs} \]  
\[ (13) \]

\[ v_{ds} + \Delta v_{ds} = r_{s} i_{ds} - \frac{\partial \psi_{qs}}{\partial \theta_{s}} + \frac{p}{\partial \theta_{s}} \psi_{ds} \]  
\[ (14) \]

\[ \psi_{0s} + \Delta \psi_{0s} = r_{s} i_{0s} + \frac{p}{\partial \theta_{s}} \psi_{0s} \]  
\[ (15) \]

\[ v_{qr} + \Delta v_{qr} = r_{r} i_{qr} + \frac{\partial (\alpha_{b} - \alpha_{r})}{\partial \theta_{r}} \psi_{dr} + \frac{p}{\partial \theta_{s}} \psi_{qr} \]  
\[ (16) \]

\[ v_{dr} + \Delta v_{dr} = r_{r} i_{dr} - \frac{\partial (\alpha_{b} - \alpha_{r})}{\partial \theta_{r}} \psi_{qr} + \frac{p}{\partial \theta_{s}} \psi_{dr} \]  
\[ (17) \]

\[ \psi_{0r} = r_{r} i_{0r} + \frac{p}{\partial \theta_{s}} \psi_{0r} \]  
\[ (18) \]

where

\[ \Delta v_{qs} = k \left( \frac{2}{3} L_{d}s + 3 L_{m}s \right) \cos \theta_{s} \frac{d}{dt} f + \left( \frac{k}{3} 2 r_{s} \cos \theta_{s} \right) f \]  
\[ (19) \]

\[ \Delta v_{ds} = k \left( \frac{2}{3} L_{d}s + 3 L_{m}s \right) \sin \theta_{s} \frac{d}{dt} f + \left( \frac{k}{3} 2 r_{s} \sin \theta_{s} \right) f \]  
\[ (20) \]

\[ \Delta v_{0s} = \frac{k^{2}}{3} L_{d}s \frac{d}{dt} f + \frac{k}{3} r_{s} f \]  
\[ (21) \]

and

\[ \Delta v_{qr} = k L_{m}s \left( \cos \theta_{s} \frac{d}{dt} f + (\alpha_{p} \sin \theta_{s} \frac{d}{dt} f ) \right) \]  
\[ (22) \]

\[ \Delta v_{dr} = k L_{m}s \left( -\sin \theta_{s} \frac{d}{dt} f + (\alpha_{p} \cos \theta_{s} \frac{d}{dt} f ) \right) \]  
\[ (23) \]

The intensity of the fault is ‘k’, which is the ratio of the number of shorted turns and the total number of turns in series per phase and \( i_{f} \) is the fault current.

It can also be shown that in the faulty loop, the voltage equation shall be:

\[ k \left( L_{d}s + L_{m}s \right) \frac{d}{dt} f + (r_{f} + k r_{s} \sin \theta_{s} i_{f} = k \left( i_{qs} \cos \theta_{s} + i_{ds} \sin \theta_{s} + i_{dl} \right) \]

\[ + \omega_{k} \left( k L_{d}s + L_{M}s \right) (-i_{qs} \sin \theta_{s} + i_{ds} \cos \theta_{s}) + k (k L_{d}s + L_{M}s) \left( \cos \theta_{s} \frac{d}{dt} i_{qs} + \sin \theta_{s} \frac{d}{dt} i_{ds} \right) \]

\[ + k^{2} L_{d}s \frac{d}{dt} i_{0} - \omega_{k} k L_{M}s (i_{qr} \sin \theta_{s} + i_{dr} \cos \theta_{s}) + k L_{M}s \left( \cos \theta_{s} \frac{d}{dt} i_{qr} + \sin \theta_{s} \frac{d}{dt} i_{dr} \right) \]  
\[ (24) \]

Also, the electromagnetic torque can be expressed as

\[ T_{e} = \frac{3}{2} \frac{p}{2} \left( \psi_{ds} l_{qs} - \psi_{qs} l_{ds} \right) + p k L_{M} i_{f} \left( i_{dr} \cos \theta_{s} - i_{qs} \sin \theta_{s} \right) \]  
\[ (25) \]

Fig. 2 shows the SIMULINK block diagram of the model of the faulty motor.
IV. Detection of the fault

An efficient and reliable way of the detection of inter-turn fault in induction motors is of great importance today. Some of the characteristics of the motor, which changes when a fault is developed, are to be identified, which can serve as the features for the fault detection. In this work, a novel method for the feature extraction for fault detection from stator current of an induction motor is proposed. It uses the wavelet transform techniques for processing the stator current data acquired during the fault condition. The trials and tribulations associated with classical signal processing techniques for non stationary signals can be avoided with this method. Main advantage of this method is that, for an induction motor with either a constant load or a varying load, this method works efficiently.

IV.1 Theory of Wavelet

To analyze a time-varying signal, several signal processing techniques based on two dimensional time-frequency domain representation have been proposed. Among them, the short-time Fourier transform (STFT) and wavelet transform (WT) have been commonly applied for machine fault diagnosis. The STFT of a discrete-time signal \( x(n) \) is defined as,

\[
STFT(k, m) = \sum_{n=0}^{N-1} x(n)w(n-m)e^{-j\frac{2\pi kn}{N}} \tag{26}
\]

where \( w(n) \) is the sliding window.

This inherent relationship between the time and frequency resolutions becomes more critical when the STFT deals with signals whose frequency content is continuously changing.

To solve the trade-off between time and frequency resolutions of the STFT, the wavelet transform (WT) has been developed. In contrast to the STFT, the WT uses short windows at high frequencies and long windows for low frequencies. Using the WT, the time-varying spectra of non-stationary signals can also been obtained in form of scalograms defined as the squared modulus of the WT.

The signal is multiplied with a function (the wavelet), similar to the window function in the STFT, and the transform is computed separately for different segments of the time-domain signal.

The wavelet function can be defined at scale ‘\( a \)’ and location ‘\( b \)’ as

\[
\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \tag{27}
\]

In discrete wavelet transform DWT, the wavelet transform of a continuous time signal \( x(t) \) is considered where discrete values of the dilation and translation parameters, ‘\( a \)’ and ‘\( b \)’ are used.

A natural way to sample the parameters \( a \) and \( b \) is to use a logarithmic discretization of the \( a \) scale and link this, in turn, to the size of steps taken between \( b \) locations. The discretization of the wavelet has the form
\[ \psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \psi \left( \frac{t-nb_0}{a_0^m} \right) \]  

(28)

Where the integers \( m \) and \( n \) control the wavelet dilation and translation respectively; \( a_0 \) is a specified fixed dilation step parameter set at a value greater than 1, and \( b_0 \) is the location parameter which must be greater than zero.

The wavelet transform of a continuous signal, \( x(t) \), using discrete wavelet of the form of equation (28) is then

\[ T_{m,n} = \int_{-\infty}^{\infty} x(t) \frac{1}{a_0^m} \psi \left( a_0^{-m} t - nb_0 \right) dt \]  

(29)

Where \( T_{m,n} \) are the discrete wavelet transform values given on a scale-location grid of index \( m,n \). For the DWT, the values of \( T_{m,n} \) are known as wavelet coefficients or detail coefficients.

The accuracy of the WT based feature extraction depends up on the selection of the base function. There are different families of wavelets that can be used for different applications. The first step of wavelet decomposition is to select an appropriate wavelet for the signal to be analyzed. Appropriate wavelets should have a wave shape, which is close to the signal to be analyzed or filtered. The application of wavelet in motor current feature extraction is described in the next section.

IV.2 Statistical parameters of wavelet coefficients

The wavelet transform is first applied to decompose the original stator current signals into frequency bands. One of the advantages of the wavelet transform is that it can decompose signals at various resolutions, which allows accurate feature extraction from non-stationary signals under dynamic load conditions. Once the wavelet coefficients at various decomposition levels are obtained for the stator current signal, the statistical parameters of them shall be obtained. The three phase motor stator currents for healthy motor as well as the faulty motor at different load conditions (ranging from no load to full load) and various fault levels were considered for the feature extraction. Detailed coefficients up to 6th level and approximation coefficient at 6th level of wavelet decomposition of the stator current signals were extracted. Statistical parameters, such as mean, median, mode, kurtosis, interquartile range, geometric mean, harmonic mean etc. were then obtained for each of these wavelet coefficients. Some of these statistical data or parameter properties shall be used to detect the inter-turn fault of the induction motor, which is explained in the next section.

IV.3 Proposed method

These statistical parameters were analysed at all decomposition levels and load level – fault level combinations for appropriate feature identification for fault detection. The purpose of the feature extraction process is to select and retain the relevant information from the signals, which in turn is used to identify the development of the fault. We have plotted these statistical parameters of detailed as well as approximation wavelet coefficients at different decomposition levels for the healthy motor as well as the motor with different levels of inter-turn fault at given load conditions. It is observed that the parameters such as mean, harmonic mean etc. are showing random variation with reference to the fault levels, which make them non-facet as far as fault detection is concerned. Some other parameters were showing regular but little variation when the fault is developed. It is observed that the interquartile range of 6th level detailed coefficient or 6th level approximation coefficient of the stator current is exhibiting regular and wide variation when the fault is developed, qualifying it as one of the best features for the inter-turn fault detection. Interquartile range is a robust estimate of the spread of the data, which is calculated as the difference between the 75th and 25th percentiles (3rd and 1st quartiles) of the wavelet coefficients.

V. HARDWARE SET UP

The hardware used to conduct the experiment consists of three subsystems: the motor under test, loading mechanism, user interface and data acquisition system. Block diagram of the overall experimental setup is illustrated in Fig. 3.
V.1 Machine set up

A three phase, three horse power induction motor with following details is used in the laboratory setup. Supply: 3 Phase, 415V, 4.5A, 50Hz, Speed: 1440 rpm stator windings are star connected. The per phase parameters obtained by conducting proper tests on the motor to are listed as: stator resistance = 3.45Ω/phase, rotor resistance = 3.33Ω/phase, stator leakage inductance = 0.0152H/phase, rotor leakage inductance = 0.0152H/phase, magnetizing inductance = 0.2876H/phase. Moment of inertia of the motor is obtained as 0.018kg.m².

The machine used in the experiment is primed for experiments by suitably tapping the stator windings to introduce inter turn faults. Different stages of alteration are shown in Fig. 4.

V.2 Current sensor kit

Three hall effect sensors are used as the transducer for the measurement of the stator current. Isolated and regulated power supplies were developed for supplying the transducer. The sensor board was calibrated for currents ranging
from minimum to maximum to ensure accuracy and linearity in the measurement. Fig.5 shows the current sensor board used for the experiment.

![Current sensor board](image1)

**Fig. 5. Three phase Current sensor board**

V.3 Data acquisition system.

Advantech PCI-1711 is a powerful data acquisition card (DAC) with a PCI interface to. It features a unique circuit design and has the complete functions required for data acquisition and control. The Advantech PCI-1711 provides users with the most requested measurement and control functions.

![Data acquisition setup](image2)

**Fig. 6 The data acquisition setup.**

The three phase stator current data acquired through DAC (Fig.6 ) and MATLAB / SIMULINK real time windows target are saved to MATLAB workspace. Then it is taken for further processing by wavelet transformation and parameter estimation.

VI RESULTS

Induction motor was modeled for the healthy as well as the stator-fault conditions and are simulated as per the equations from (1) – (12) and (13) - (25) respectively using Matlab Simulink. The stator current waveforms were obtained from this model and then their wavelet coefficients were calculated, statistical parameters of them were determined and plotted to identify the features. The fault was physically created in the experimental setup of the motor, whose current waveforms were acquired through current transducer and DAC and the wavelet coefficients of these stator currents were calculated.

It can be seen that the results obtained from simulation closely matches with those of the hardware setup, undoubtedly confirming the inter-turn fault modeling.

VI.1 Simulation results

An induction motor with parameters given in previous section is used in the simulation for identifying the trends in the features that are extracted for fault detection. The waveforms of the stator current, the wavelet coefficients, and torque & speed variations at various load and fault conditions obtained from simulation are shown in Fig. 7 to 13.
Fig. 7. Stator currents under inter turn fault condition.

Fig. 8. Wavelet decomposition of the stator current under healthy no load condition.

Fig. 9. Speed and Torque of healthy motor under Constant load.
Fig. 10. Torque and speed of healthy motor for pulsed load.

Fig. 11. Torque and speed of healthy motor under ramping up load.

Fig. 12. Speed and Torque of faulty motor at 3A load.
The stator current spectra which are obtained under healthy and faulty conditions are shown in Fig. 14-16. Here, 1024 point radix-2 FFT algorithm is used for estimating the power spectral density (PSD).

VI. Experimental results

The spectra of the stator currents drawn by the motor in the experimental setup acquired through DAC under healthy and faulty conditions for three different loading patterns are shown in Fig. 15 to 17.
Fig. 14 – 16 shows that PSD cannot be used as a pertinent feature for determining the internal faults of the machine under real time dynamic situations. It is under this context that the method proposed in this paper has gained significance.

Plot of harmonic mean and interquartile range of six levels of Detailed Wavelet Coefficients (cD1-cD6) as well as Approximation Coefficient at sixth level (cA6) for three phases at no load, 3Amp and full load (4.5Amp) at different fault levels obtained from stator current in the simulation setup are given in Fig. 17 and Fig. 18 respectively. Corresponding plots obtained from hardware setup are shown in Fig.19 and 20 for the stator three phase currents, R, Y and B.
Fig. 17 Simulation Result :: Harmonic mean of Detailed coefficients (cD1 – cD6) and the Approximation coefficient (cA6) at full load, 3A load and no load for various fault levels for R, Y and B phase currents obtained from Simulation. Data points 1&2 belongs to healthy motor, 3&4 for the faulty motor with 150kΩ fault resistance 5&6 are faulty motor with 1kΩ fault resistance and 7&8 are faulty motor with 100 Ohm fault resistance.
Fig. 18 Simulation Result: Interquartile range of Detailed coefficients (cD1 – cD6) and the Approximation coefficient (cA6) at full load, 3A load and no load for various fault levels for R, Y and B phase currents. Data points 1&2 belong to healthy motor, 3&4 for the faulty motor with 150k fault resistance, 5&6 are faulty motor with 1k fault resistance, and 7&8 are faulty motor with 100 Ohm fault resistance. Note that the fault is made in 'Y' phase.
Fig. 19 Harmonic mean of Detailed coefficients (cD1 – cD6) and the Approximation coefficient (cA6) at full load, 3A load and no load for various fault levels for R, Y and B phase currents obtained from Hardware setup. Data points 1&2 belongs to healthy motor, 3&4 for the faulty motor with 150k fault resistance and 5&6 are faulty motor with 1k fault resistance.
Fig. 20 Interquartile range of Detailed coefficients (cD1 – cD6) and the Approximation coefficient (cA6) at full load, 3A load and no load for various fault levels for R, Y and B phase currents obtained from Hardware setup. Data points 1&2 belongs to healthy motor, 3&4 for the faulty motor with 150k fault resistance and 5&6 are faulty motor with 1k fault resistance. Note that the ‘Y’ phase is the faulty one.

From Fig. 17 – 20, it may be noted that the deviation in Harmonic mean is at a random fashion whereas the interquartile range shows an expected and orderly variation, when the fault is developed. The maximum distinction is observed in the case of cD6, the sixth level Detailed Wavelet Coefficient. Interquartile range of the cD6 coefficient corresponding to the stator current of the faulty phase (Y Phase here) decreases as the fault is developed in the motor and it increases for the currents in other two functional phases (R and B Phases, which do not have the fault).

The proposed method can clearly distinguish between the healthy and faulty condition of the induction machine. The results obtained from laboratory setup follow the same trend as that gained from simulation, verifying the model’s meticulousness. It can be seen from these experimental and simulation results that the proposed method could be used for the detection of inter-turn fault of an induction motor. By continuously monitoring the interquartile range of the sixth level detailed wavelet coefficient of the stator currents, the inter-turn fault was detected in its development stage itself.

VI. CONCLUSION

It is established from the simulation results, which was later proved experimentally, that the new technique for the inter turn fault detection of the induction motor using the interquartile range of the wavelet coefficient of the stator current is very effective and efficient. The inter turn fault of the induction motor was modelled mathematically. This mathematical model was used for the simulation of the inter-turn fault of the induction motor in SIMULINK (Matlab) platform, which was used to obtain the first level information regarding the stator current characteristics as well as the variation in speed, torque, etc. under healthy as well as faulty conditions of induction motor. The stator currents obtained under various load and fault conditions were decomposed using wavelet transform whose statistical parameters were then obtained. It is observed that many of the statistical parameters were showing random variation and only few of them shows variation as we are seeking. The healthy and faulty operation of the induction motor was clearly distinguished using the feature mentioned above. The results obtained from simulation were experimentally verified in the laboratory. It is observed that the variation in interquartile range resulted from the inter-turn fault obtained from simulation matches closely with the experimental results. As a future work, it is suggested that this feature can be used in algorithms such as support vector machine or naive Baye’s so that the real-time fault monitoring can be implemented with a much higher reliability grade to detect the fault in its development stage itself.

REFERENCES


Nomenclature

- $V_d$: Direct Component of voltage
- $V_q$: Quadrature Component of voltage
- $P_B$: base power of the machine
- $N_s$: number of turns in stator per phase
- $\lambda$: flux linkage
- $H$: inertia constant
- $p$: differential operator
- $T_L$: load torque
- $\omega_p$: base speed
- $T_f$: frictional torque
- $E_n(s)$: wavelet energy
- $E(s)$: Shannon entropy
- $r_s$: stator resistance per phase

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