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A review of health monitoring techniques of induction Motor

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Induction motor is singly excited and brushless,very simple, compact and extremely rugged in construction and most reliable and low cost motor. Although, these motors are reliable but often exposed to hostile environments during its operation which leads to early deterioration leading to the motors failure. Faults and failures of induction machines can lead to excessive downtimes and generate large losses in terms of maintenance and revenues. This paper deals with the study of identification of different type of faults and the health monitoring techniques commonly used in induction motors.

Keywords: *Faults, health monitoring, fault diagnostic technique, induction motor.*

1.0 INTRODUCTION

Although Induction motors are highly reliable industrial drive, these motors are often exposed to hostile environments during operation which leads to early deterioration leading to the motor failure. Faults and failures of induction machines can lead to excessive downtimes and generate large losses in terms of maintenance and lost revenues. Even small fault can causes increased losses such as reducing efficiency and increasing temperature, which will reduce insulation lifetime, and increasing vibration, in turn may reduce bearing life time. All they are due to the operating environment condition and machine internal factors. The proper study and knowledge of motor faults are very essential, then only we can go for the condition monitoring of motor and proper diagnosis of the problem which prevent the expensive maintenance cost. Knowledge of health monitoring technique is also essential for the continuous monitoring of the health of the motor, so that the fault can be identified at the earlier stage itself. Diagnostic technique is also an important part of motor prevention because unless the correct fault is not diagnosed, we can't go for its early stage protection.

2.0 DIFFERENT TYPES OF FAULTS IN INDUCTION MOTOR

A statistical study in 1985 was conducted by Electric Power Research Institute (EPRI) provides and found as bearing faults(41%), stator faults (37%), rotor faults (10%) and others (12%). According to IEEE standard 493-1997, the most common faults and their statistical occurrence are tabulated in Table -1 and Figure 1. This IEEE statistics of induction motor faults are almost matched with EPRI data [1, 2].

TABLE 1
STATISTICS OF INDUCTION MOTORS FAULTS AND FAILURES [2]

	IEEE-IAS (%) Electrical Safety Workshop	IEEE-IAS (%) Electrical Safety Workshop	EPRI (%) Electrical Power Research Institute
Number of faulty motor	380	304	1052
Bearing-related	44	50	41
Winding-related	26	25	36
Rotor-related	8	9	9
Other	22	26	14

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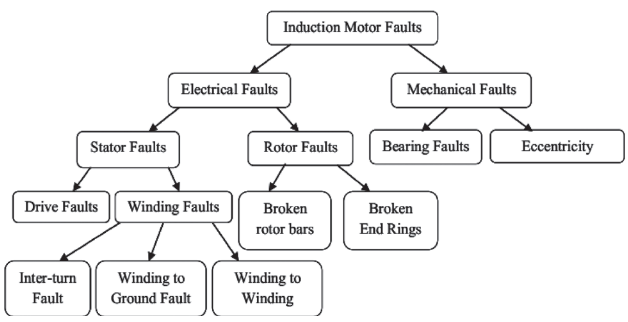

FIG. 1 TYPES OF FAULTS IN INDUCTION MOTOR

A. Stator faults

According to published surveys, Induction motor short turn (stator winding) failure is in the range of 30-40% of the total failure. Moreover it is generally believed that a large portion of the stator winding related failures are initiated by insulation failures in several turns of the stator coil within one phase. This type of the fault is known as stator inter turn fault. Inter-turn short circuits in stator windings constitute a category of faults that is most common in induction motors. Typically, short circuits in stator windings occur between turns of one phase, or between turns of two phases, or between turns of all phases. Moreover, short circuits between winding conductors and the stator core also occur known as winding to ground fault [3,28]. There may be different types of short circuit faults such as (i) inter turn fault (ii) winding to ground fault and (iii) winding to winding fault[31].

B. Rotor fault

Squirrel cage of an induction motor consists of rotor bars and end rings. Usually lower rating machines are manufactured by die casting techniques where as high ratings machines are manufactured with copper rotor bar. Rotor cage fault (broken rotor bar/end-ring) accounts for approximately 5-10% of all induction motor failures [4]. For any medium size motors, the rotor cage fault is even more common than that of small motors, due to the extensive thermal stresses on the rotor. Reason of the rotor fault may be due to either rotor bar may be unable to move longitudinally in the slot it occupies or the large centrifugal force or non uniform metallurgical stresses during manufacture. There may be two types of breakage of bar one is Breakage of skewed bars and other is Breakage of end-rings[27].

C. Load faults

In some particular application such as aircrafts, the reliability of gears and load faults may be critical in safeguarding human lives. Due to that the detection of load faults (especially related to gear) has been an important factor of research. Motors are often coupled to mechanical loads and gears. Several faults are also can occur in mechanical arrangement. Examples of such faults are coupling misalignments and faulty gear systems that couple a load to the motor [5].

D. Air gap eccentricity

Air gap eccentricity, a common rotor fault, is the situation when the air gap between the stator and rotor is unequal. Severe air gap eccentricity may lead to unbalanced magnetic pull and eventually result in the rotor to stator friction which make the machine vibrating and produced noise. This can be responsible for the damage of the stator and rotor core. There are three types of air gap eccentricity (i) Static eccentricity (ii) Dynamic eccentricity and (iii) Mixed eccentricity

In static eccentricity, the rotor rotates around its natural axis which is inclined compare to the stator one. Static eccentricity is a steady pull in one direction which creates unbalanced magnetic pull (UMP). UMP caused by static eccentricity may lead to bend rotor shaft, bearing failures, dynamic eccentricity and eventually stator to rotor rub, causing a major breakdown of the motor.

In dynamic axial eccentricity, the rotor natural axis inclined compare to its rotational axis, which is superimposed to the stator axis. Dynamic eccentricity produces an unbalanced magnetic pull that rotates at the rotational speed of the motor and acts directly on the rotor. This makes the unbalanced natural pull in a dynamic eccentricity easier to detect by vibration or current monitoring.

The combination of static and dynamic eccentricity is called mixed eccentricity [6].

E. Bearing faults

Rolling – element bearings are overwhelmingly used to provide rotor support. The rolling-element bearing in an induction motor is one of the most critical components because bearing related failures have been accounted for 41% of all failures. Moreover, bearing fault in an induction motor may be responsible later for winding failure. Hence, incipient detection of bearing fault is crucial for prevention of drive failures. Bearing fault can be classified as: (i) single- point-defects and (ii) generalized roughness [7, 33, and 36].

3.0 HEALTH MONITORING TECHNIQUE FOR INDUCTION MOTOR

Health monitoring can be explained as the continuous evaluation of the health of induction motor during its working. It is important to detect faults while they are developing which is called incipient failure detection. Incipient failure detection can provide safe operating environment.

A. Thermal Monitoring

Thermal monitoring of induction motor can be performed either by measuring the local or bulk temperatures of the motor or by parameter estimation (Figure 2). A stator winding faults produce huge heat and the amount of heat indicate the severity of the fault until it reaches at a dangerous level. Stator thermal overload has drawn a lot of attention in the past several decades, as it is one of the root causes for the stator insulation failure. Different types of relays have been developed to provide thermal protection and overload protection for induction motors. Embedded thermal sensors are broadly used for MV large motors, to monitor the temperature of the stator winding to avoid thermal overload. Thermal protection for the rotors of these motors is necessary for reducing bearing and rotor cage failures [8,30].

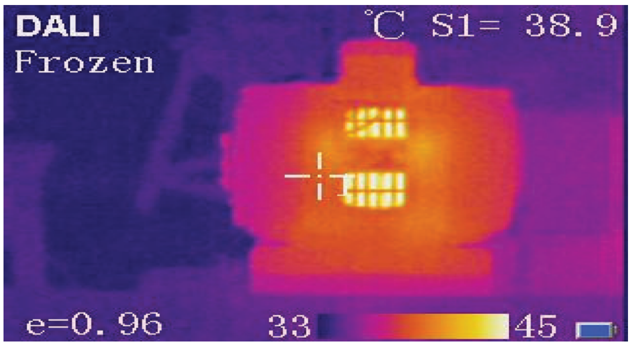

FIG. 2 THERMAL PROFILE OF IM

B. Vibration Monitoring

Each electrical machine has its own vibration signature and analysis of vibration can be used to monitor the condition of motor performance (Figure 3). Vibration of the machine has certain relation with its noise. Even small amplitude of vibration can produce a huge noise for the machine. Noise and vibration in the electric machines are caused by the forces which are magnetic, mechanical and aerodynamic origin.

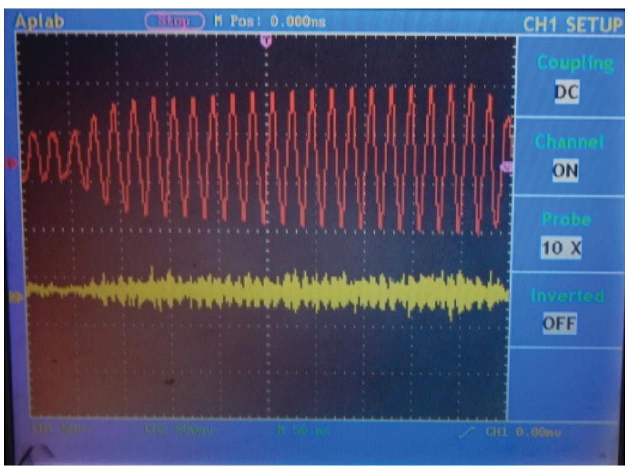

FIG. 3 CURRENT AND VIBRATION SIGNATURES OF IM UNDER SINGLE PHASING

The vital reason of vibration in the electrical machine is radial force due to air gap field. In the mechanical monitoring, vibration based condition monitoring has attracted the attention of many researchers working in the area of induction machines and has gained industrial acceptance, as vibration analysis techniques are more effective in assessing a machine's health. Newly made electrical machines also generate some level of vibration. Vibration monitoring is based on vibration transducers, virtual measuring accelerometers of piezo-resistive types with linear frequency spectrum, normally placed on the bearings for detecting mechanical faults. [9].

C. Torque Monitoring

All type of motor faults produces the side bands at special frequencies in the air gap torque. Presently the commercially available methods for detecting rotor bar defects of induction motors are based on various identifications of side bands of a line current. This study suggests a new method for detecting not only the rotor defects but also the stator shorted coils. Air-gap torque is the torque produced by the flux linkages and the currents of a rotating machine. Air-gap torque can be measured while the motor is running. No down time is required for its measurement. This can be financially attractive to many industries, where an unscheduled down time of a motor posts a heavy loss in the operation of a production system. Because the rotor, shaft and mechanical load of a rotating machine constitute a specific spring system that has its own natural frequencies, the attenuations of the torque components of the air-gap torque transmitted through the spring system are different for different harmonic orders of torque components. From the input terminals, the instantaneous power includes the charging and discharging of the energy in the windings [10]. That‘s why the instantaneous power cannot represent the instantaneous torque. Generally speaking, the waveform of the air-gap torque curve is different from that of the torque measured from the shaft [35, 36].

D. Noise Monitoring

Noise monitoring can be done by measuring and analyzing the acoustic noise spectrum from the induction machines. Acoustic noise from air gap eccentricity is helpful to detect the faults of the induction motor. However this method is not very much useful in large industry because of the noisy atmosphere will disturb the original sound produced by the machine. As a result it‘s very difficult to get accurate reading described the method to calculate the air gap eccentricity by using noise signature. They have conducted the test in an anechoic chamber and verified that the slot harmonics in the anechoic noise spectra from a small power induction motor were functions of static eccentricity [23].

E. Electrical Monitoring

There are different types of electrical monitoring techniques described by the researchers. They are discussed below one by one.

a) Current Signature Analysis:

Large machine are often equipped with mechanical sensors, primarily vibration sensors based on proximity probes. But they are very delicate and expensive. Moreover, in many situations, vibration monitoring methods are utilized to detect the presence of incipient failure. However, it has been suggested that stator current monitoring can provide the same indications without requiring access to the motor. Therefore, the researchers are concentrated their research on the so-called motor current signature analysis. This technique utilizes results of spectral analysis of the stator current (precisely, the supply current) of an induction motor to spot an existing or incipient failure of the motor or the drive system. Spectral analysis of the stator current allows obtaining a characteristic spectral signature which can be easily distinguished from abnormal operating condition and then identified as a potential failure mode. Some of the faults can be analyzed by the above methods are broken bars in the rotor cage, rotor eccentricity, worn or damaged bearings, shaft speed oscillation, and electrical-based faults (unbalance voltage and single-phasing effects). Experimental investigations, for high-resolution analysis, have been carried out only for electrical-based faults detection and localization [11,30].

b) Current Park's Vector:

Another important electrical monitoring technique is Current Park‘s vector technique. The basic concept of Current Park‘s vector technique is the connection to stator windings of a three phase induction motor generally does not use a neutral. The stator current has no zero sequence components for star connected induction motor. Current park‘s vector is the two dimensional representation of three phase current. This current park‘s vector is regarded as the description of motor condition. Under ideal condition balanced three phase currents lead to a park‘s vector that is a circular pattern centered at the origin of coordinates. Therefore the motor condition can be monitored and presence of the fault can be detected by monitoring the deviation of Current Park‘s vector [12]. In some papers various applications of artificial neural networks (ANNs) prove that such technique is well suited to cope with online fault diagnosis in induction motors. The proposed methodology is based on the so -called Park’s vector approach. In fact, stator current Park’s vector patterns are first trained, using artificial ANN, and then used to discern between ‘healthy’ and ‘faulty’ induction motors. The obtained results provide a satisfactory level of accuracy, indicating a promising industrial application of the hybrid Park’s vector-neural networks approach. In few papers, the subject of on-line detection and location of inter -turn short circuits in the stator windings of three-phase induction motors is discussed, and a noninvasive approach, based on the computer aided monitoring of the stator current Park’s vector, is introduced. The researchers are also shown the experimental results, obtained by using a special fault producing test rig and hence effectiveness of the proposed technique is proved. In [13,26] on-line detection of rotor cage faults in three-phase induction motors is discussed, and a noninvasive approach, based on computer-aided monitoring of the stator current Park’s vector, is introduced. Both simulation and laboratory test results are shown to prove the effectiveness of the proposed technique, for detecting broken rotor bars or end-rings in operating three-phase induction machines [31].

4.0 DIAGNOSTIC TECHNIQUES FOR INDUCTION MOTOR FAULTS

Different techniques are used to diagnosis the faults of induction motor are discussed here:

A. Model based techniques:

Model based diagnosis defines an asymmetrical induction motor whose model is used to predict failure fault signatures. The difference between measured and simulated signatures is used as a fault detector. Many papers discuss a low order differential model and through which mathematical analysis is introduced for induction machine for faulty stator. An adaptive Kalman filter is proposed for recursively estimating the states and parameters of continuous-time model with discrete measurements for fault detection ends. Typical motor faults as inter-turn short circuit and increased winding resistance are taken into account. Researchers proposed a new frequency analysis of stator current to estimate fault-sensitive frequencies and their amplitudes for broken rotor bars (BRBs). The proposed method employs a frequency estimator, an amplitude estimator, and a fault decision module. Researchers explained rotor fault detection system based on multi-sensor data fusion estimation of induction motor model, which makes use of strong tracking ability to the abrupt state. Due to the soft computing era there is a trend to make the mathematical modeling of the machine and through the parameter estimation technique the different faults are diagnosed. This parameter estimation is a novel technique which helps us not only to diagnose the fault, but also provides accurate and fast detection. Model based technique has been implemented in two ways (a) parameter/state estimation method and (b) residual generation method [14, 32].

B. Signal Processing Techniques

Signal based diagnosis relies on advances in digital technology. It looks for known fault signatures in quantities sampled from the actual machine. The signatures are then monitored by suitable signal processors. Signal processing can be used to enhance signal to noise ratio (SNR) and to normalize data in order to isolate the fault from other phenomena and decrease sensitivity to operating conditions. Data based diagnosis does not require any knowledge of machine parameters and model. It relies only on signal processing and on clustering techniques. Signal processing techniques can be further divided into different subclasses. The subclasses are shown here and discussed individually [15,37] (i)Spectrum through Frequency Domain Method (a) Fast Fourier Transform (FFT) (ii) Spectrum Through Time Frequency Domain method (a) Short Time Fourier Transform (STFT) (b) Gabor Transform (GT) (c) Winger-Ville Distribution (WVD) (iii) Wavelet Transform

C. Fast Fourier Transform (FFT)

Although Discrete Fourier Transform (DFT) is the most straight mathematical procedure for determining frequency content of a time domain sequence, but it is terribly inefficient. As the number of points in the DFT is creased to hundreds or thousands, the amount of necessary number crunching becomes excessively large. Hence, modified algorithm is proposed and it is known as the Fast Fourier Transform (FFT). A lot of intensive research has been done on the motor current signature analysis. This technique utilizes the results of spectral analysis of the stator current. Reliable interpretation of the spectra is difficult, since distortions of the current waveform caused by the abnormalities in the drive system are usually minute. Benbouzid M. E. H. used the frequency signature of asymmetrical motor faults are well identified using the fast Fourier transform (FFT), leading to a better interpretation of the motor current spectra. It is shown that the motor current signature FFT-based analysis is still reliable tool for induction motor a symmetrical faults detection. In the some papers statistical time-domain techniques are used to track grid frequency and machine slip. Here either a lower computational cost or a higher accuracy than traditional discrete Fourier transform techniques can be obtained. Then, the knowledge of both grid frequency and machine slip is used to tune the parameters of the zoom fast Fourier transform algorithm that either increases the frequency resolution and/or reducing the computational cost. The proposed technique is validated for rotor faults. Traditional analysis methods, based on the fast Fourier transform (FFT), have some limitations, such as diagnosis under low load conditions, due to the spectral leakage effect, or the need of using long time samples for achieving sufficient resolution in the frequency domain [16].

D. Gabor transforms:

Gabor transform (GT) is a liner time-frequency analysis method that computes a liner time frequency representation of time domain signal. Gabor spectrogram has the better time frequency resolution than that of STFT spectrogram method. Gabor spectrogram can be used for fault diagnosis of induction motor. Time-frequency analysis of the transient current in induction motors (IMs) is the basis of the transient motor current signature analysis diagnosis method. IM faults can be accurately identified by detecting the characteristic pattern that each type of fault produces in the time-frequency plane during a speed transient. A fine tuning of their parameters is needed in order to obtain a high-resolution image of the fault in the time-frequency domain, and they also require a much higher processing effort than traditional diagnosis techniques. The new method proposed in the paper [17] addresses both problems using the Gabor analysis of the current via the chirp z-transform, which can be easily adapted to generate high-resolution time-frequency stamps of different types of faults. Here, it is used to diagnose broken bars and mixed eccentricity faults of an IM using the current during a startup transient.

E. Winger-Ville Distribution (WVD)

Refaatetal. [24] developed a novel, non-intrusive approach for fault -detection and diagnosis scheme of bearing faults for three-phase induction motor using stator current signals with particular interest in identifying the outer-race defect at an early stage. The empirical mode decomposition (EMD) technique is proposed for analysis of non-stationary stator current signals. The stator current signal is decomposed in intrinsic mode function (IMF) using empirical mode decomposition. The extracted IMFs apply on the Wigner-Ville Distribution (WVD) to have the contour pattern of WVD. Then, artificial neural network is used for pattern recognition that can effectively detect outer-race defects of bearing. The experimental results show that stator current-based monitoring with WVD based on EMD yields a high degree of accuracy in fault detection and diagnosis of outer-race defects at different load conditions [18].

F. Soft computing Techniques

Soft Computing Techniques (Artificial Neural Networks, Fuzzy Logic Models, and Adaptive Neuro Fuzzy inference system) have been recognized as attractive alternatives to the standard, well established —hard computing paradigms.

a) Artificial Neural Network Technique

A neural network can substitute in a more effective way the faulted machine models used to formalize the knowledge base of the diagnostic system with suitably chosen inputs and outputs. Training the neural network by data achieved through experimental tests on healthy machines and through simulation in case of faulted machines, the diagnostic system can discern between "healthy" and "faulty" machines. This procedure substitutes the statement of a trigger threshold, needed in the diagnostic procedure based on the machine models. Many research papers presented in the past for monitoring and fault identification of a three-phase induction motor using artificial neural networks (ANNs). Three-phase currents and voltages from the induction motor are used in the proposed approach. A feed forward multi-layered neural network structure is used. The network is trained using the back propagation algorithm. The trained network is tested with simulated fault current and voltage data. In some papers a protection scheme based on Wavelet Multi Resolution Analysis and Artificial Neural Networks are proposed which detects and classifies various faults like Single phasing, Under voltage, Unbalanced supply, Stator Turn fault, Stator Line to Ground fault, Stator Line to Line fault, Broken bars and Locked rotor of a three-phase induction motor[19,27,29].

b) Fuzzy Inference system

Fuzzy logic is a type of mathematics and programming that helps the making a model by using learning and experience for representation of vague concepts in mathematical expressions. Therefore, fuzzy systems are very useful in situations involving highly complex systems whose behaviors are not well understood and in situations where an approximate, but fast, solution is warranted. Fuzzy systems are robust because the system has been designed to control within some frame of uncertain conditions. In many papers, fuzzy logic-based induction motor protection systems was developed [19]. The motor condition is described using linguistic variables. Fuzzy subsets and the corresponding membership functions describe stator current amplitudes. A knowledge base comprising rule and data base is built to support the fuzzy inference. The induction motor condition is diagnosed using a compositional rule of fuzzy inference. In fact, fuzzy logic is reminiscent of human thinking processes and natural language enabling decisions to be made based on vague information. In the paper [2] presents the implementation of broken rotor bar fault detection in an inverter-fed induction motor using motor current signal analysis (MCSA) and prognosis with fuzzy logic. In some of the papers show the application of fuzzy logic based artificial intelligence procedures to the development of a novel method for the condition monitoring and fault diagnosis of induction motors. The finite element method (FEM) is utilized to generate virtual data that support the construction of the membership functions and give the possibility to online test the proposed system. The layout has been implemented in MATLAB/SIMULINK with both data from a FEM motor simulation program and real measurements. The proposed method is simple and has the ability to work with variable speed drives [24,29].

c) Adaptive Neuro Fuzzy Inference System (ANFIS)

ANFIS uses fuzzy Sugeno model as fuzzy inference system incorporated with ANNs training. It maps inputs through input membership function, rules, normalization and output membership function to output membership functions. Jang and Sun introduced the adaptive neuro-fuzzy inference system (ANFIS) in 1995. This system is called as hybrid system because it uses two different training rules to reduce the error. For ANFIS system, it uses a gradient descent algorithm training paradigm and a least square algorithm to tune the parameter of the membership function [19, 20]. Fuzzy logic systems lack ability of self learning and fuzzy membership functions and fuzzy rules cannot be guaranteed to be optimal. Fusion of neural network and fuzzy logic like Adaptive network based fuzzy inference system and fuzzy adaptive learning control/decision network partly overcome the problem with reducing convergence time. Genetic Algorithm can also be used to optimize the parameter and structure of neural network and fuzzy logic systems. In the paper an overview of complete current based noninvasive monitoring and protecting techniques for stator rotor, bearing and thermal overload related failure is presented. Some researchers investigate the fault diagnosis for open-switch Damages in a voltage fed PWM motor drive system. Researchers proposed a robust diagnosis method based on the Neuro-Fuzzy algorithm. For this, the Clustering Adaptive Neuro Fuzzy Inference System(C-ANFIS) has been adopted to recognize the various and vague fault patterns [19,29].

G. Wavelet Transform Analysis

The wavelet transform method can nicely be utilized for online fault detection. This method has good sensitivity and short detection time. In this method the entire signal can be reconstructed from the sets of local signals by varying scale and amplitude, but constant shape. In some papers motor current signature analysis (MCSA) is used an often cited. In this method it uses the results of spectral analysis of the stator currents. Generally the FFT (Fast Fourier transform) is used to obtain the power density vs. frequency plots to be analyzed. Here the use of a novel versatile tool of harmonic analysis, of the wavelet transform is utilized. The proposed wavelet based detection method shows a good sensitivity and reliability. In order to overcome the problems of the FFT based technique, the Short Time Fourier Transform (STFT) method was proposed. The STFT method also suffered from the drawback that it shows the constant window for all the frequencies. Therefore, it shows poor frequency resolution. In order to overcome all the problems stated so far, the most recent powerful mathematical tool i.e. Wavelet Transform (WT) has been used in the rotor broken bar fault detection purpose at all loading conditions. Ibrahim et al.[21] presented an effective method to detect broken rotor bars fault in the induction motors. This method is based on the analysis of the q-component of the stator current and discrete wavelet transform (DWT). Using the dynamic model of the squirrel-cage induction motor taking account the broken rotor bars. The RMS values of the discrete wavelet transform coefficients are fed to the artificial neural network (ANN) to identify the machine state. In the papers [22] has proposed a simulation model with the help of experimental result and presents a fault detection techniques using direct wavelet transform (DWT). In some papers, the stator current is analyzed via wavelet packet decomposition to detect bearing defects [25, 33, 34].

5.0 CONCLUSION

The paper deals with the study of different types of faults of induction motor and their diagnostic techniques. The health of induction is monitored using different techniques including modern intelligent techniques have been discussed. Different inputs may be considered for health monitoring system of Induction motor such as current signature, sound or vibration signature, Temperature profile of induction motor etc. These input signatures are analyzed using various soft computing techniques for predicting the health of induction motor.

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