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Fault Diagnostic And Monitoring Methods of Induction Motor: A Review

Anil, Kumar. Department of Electronics, India

Research Article

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Abstract

Transportation, mining, petrochemical, manufacturing, and almost every other industry using electricity utilize induction motors extensively. These motors provide a very high level of dependability since they are straightforward, effective, strong, and durable. However, just like any other machine, they are susceptible to malfunctions that, if ignored, might eventually cause the system to collapse catastrophically. Fault detection has made extensive use of online condition monitoring of induction motors. In order to identify future research opportunities, this article explores the many types of faults and studies both traditional and novel methods for induction motor problems.

Keywords

Fast Fourier Transforms, Fuzzy Logic, Artificial Neural Networks, Computer Simulation, Data Acquisition, Induction Motors, Parameter Estimation, Vibration Measurement, and Wavelet Transforms

Introduction

Every industry relies heavily on induction motors. However, heavy-duty cycles, unfavorable operating conditions, installation and manufacturing issues, etc., will ultimately lead them to fail, just like any other machine. The area of problem diagnostics in induction motors is becoming more significant due to the growing demands for efficiency and dependability. Failure to anticipate the issues might lead to significant income losses and jeopardize operational safety and dependability. Nonetheless, a variety of techniques have been put forward for defect diagnosis and detection; however, the majority of these techniques need a high level of skill to implement effectively. To allow even inexperienced operators with little system understanding to scan the problem situation and make trustworthy judgments, simpler methods are required.

Primary faults and associated secondary faults may affect an induction motor. The origins of induction motor defects are categorized in Fig. 1 (a). The internal fault tree for an induction motor is shown in Fig. 1(b), whereas the external fault tree is shown in Fig. 1(c).

In general, an induction motor may experience an external or internal problem. A defect might have an electrical or mechanical cause. Depending on where the problem is located, it might be categorized as either a rotor or stator defect. defects related to the moving components, such as bearings

and rotor defects include cooling issues [1]. In particular, bearing failures, stator faults, rotor faults, air gap eccentricity, mechanical vibrations, etc. may all be roughly categorized as induction motor problems. The relative likelihood of different faults occurring in an

induction machine is shown in Fig. 2 [2].

This study offers a thorough examination of techniques for identifying problems with induction motors and suggests topics for further investigation. Predicting early machine defects requires the use of systematic methodologies.

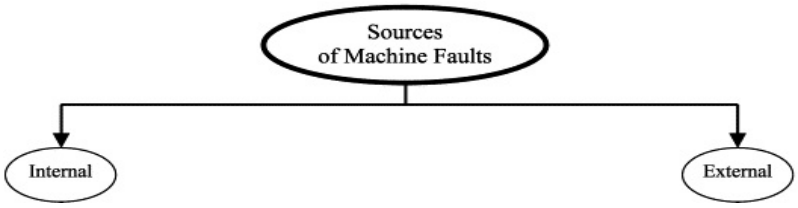


Fig.1(a) Sources of Machine Faults

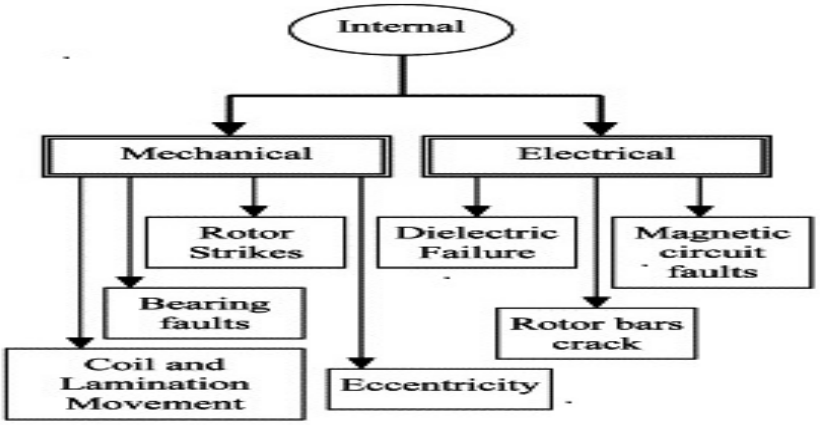


Fig. 1(b) Block Diagram Presentation of Internal Faults

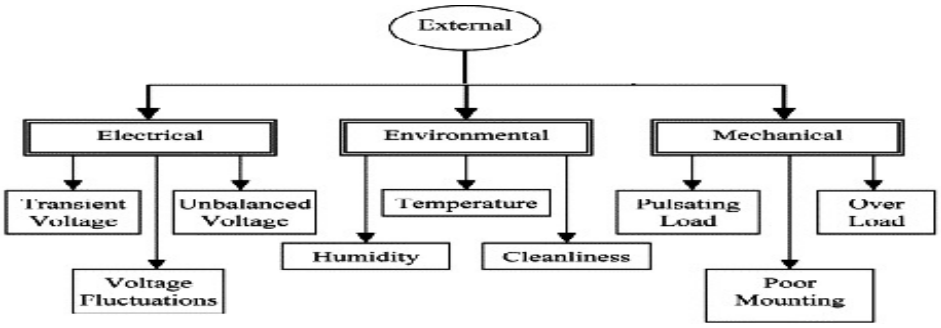


Fig. 1(c) Block Diagram Representation of External Faults

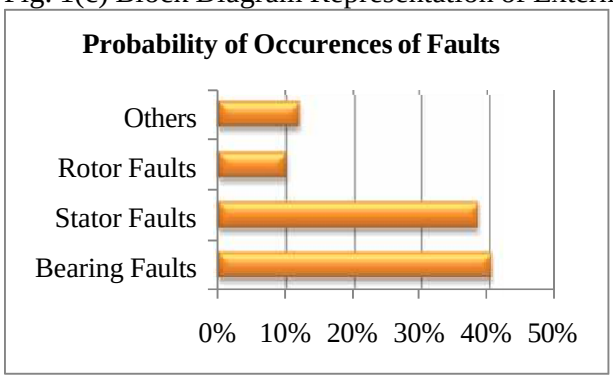


Fig.2. Faults by % in an Induction Motor

A typical diagnosis system [3] shown in Fig. 3 consists of a sensor assembly which provides the fault signal to a signal processing unit, which further sends its result to be analyzed by expert systems, where the corresponding fault is ultimately detected.

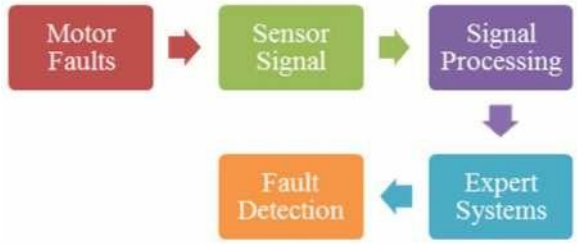


Fig. 3. On-Line Fault Monitoring of Induction Motor

Investigating the accompanying abnormalities in machine current, voltage, and leakage flux is typically how condition monitoring and fault diagnostics are accomplished. Other techniques [4-5] that have been reported to identify fault situations including insulation faults [6], partial discharge [7], and lubrication fluid and bearing deterioration [8] include monitoring the core temperature, bearing vibration level, and pyrolyzed products.

Fast Fourier Transform Spectral Signature analysis [9–11], vibration analysis [12–13], temperature measurements [14–16], harmonic analysis of speed fluctuations [17–19], state or parameter estimation [20–22], axial flux or air gap torque analysis [23–25], acoustic noise arrangement [26–27], magnetic field analysis [28–30], fuzzy logic and neural networks [31–33], etc.

Induction Motor Faults

Induction motor failure diagnostics has received significant attention. Induction motor problems are primarily classified into the following five types based on the area in which they occur.

Bearing Faults

A rolling-element bearing typically consists of two concentric rings. Between the inner and outer rings, a group of balls or rollers rotate in raceways. There are two types of bearing faults [34]: "distributed" and "local." Misaligned races, waviness, surface roughness, and off-size rolling elements are examples of distributed flaws. Spalls, pits, and fissures are examples of localized flaws.

on the surfaces that roll. The location, speed, and bearing size of the anomaly determine the period and amplitude of the impact vibrations that these localized flaws produce when a rolling roller passes over their surface. The defective bearings cause mechanical vibrations. These vibrations occur at each component's rotating speed. The characteristic frequencies linked to the raceways and the balls or rollers are determined by the machine's rotational speed and bearing diameters. By looking at these frequencies, the bearing's condition may be determined. Mechanical vibration analysis methods are used to do this job.

Stator Faults

Thermal, electrical, mechanical, and environmental stressors may all affect an induction motor [35–37]. Such demanding operating conditions are responsible for the majority of stator problems. Among the most common and possibly harmful errors in the stator winding are turn-to-turn, coil-to-coil, open circuit, phase-to-phase, and coil-to-ground [38]. If ignored, they might ultimately lead to the motor's catastrophic breakdown. The following are the three primary categories of stator defects covered in [39].

Frame :

Vibration
Circulating currents
Earth faults
Loss of coolants

Lamination:

Core slackening
Core hot spot

Stator windings faults:

End winding portion (turn-to-turn faults , fretting of insulation, local damage to insulation, damage to connectors, discharge erosion of insulation, displacement of conductors, contamination of insulation by moisture, oil or dirt, cracking of insulation and so forth).
Slot portion (insulation fretting, displacement of conductors).

Rotor Faults

Mechanical issues like rotor eccentricity or electrical failures like bar defects or bar breakage may cause rotor faults [40]. Thermal strains, hot spots, or fatigue stresses during brief operations like

start-up—particularly in big motors—cause the initial defect. A broken bar drastically alters torque, endangering the reliable and safe functioning of electric machinery [41]. Air gap eccentricity is associated with the second kind of rotor defect. This defect is often caused by a variety of technical issues with induction motors, including shaft misalignment and load imbalance. Long-term load imbalance may affect air gap symmetry and harm the bearings and bearing housing. Horizontal, vertical, or radial misalignment between a shaft and its linked load is referred to as shaft misalignment. A steady radial force caused by shaft misalignment will cause the rotor to move from its usual position.Eccentricity Faults
An induction motor's eccentricity is caused by an uneven air gap between the stator and rotor [42]. Static and dynamic air-gap eccentricity are the two main forms of air-gap eccentricity. There have also been accounts of the axial nonuniformity of the air gap, known as inclined eccentricity [44], and a combination of both kinds, known as mixed eccentricity [43]. For static air-gap eccentricity, the minimum radial air-gap length is set in space. Conversely, with dynamic eccentricity, the center of rotation and the center of rotor do not line up. In this instance, the minimal air gap location rotates with the rotor rather than being fixed in space. Static eccentricity may result from improper rotor or stator placement during the commissioning stage. The ovality of the stator core might possibly be the reason. A bent shaft, bearing wear and movement, or mechanical resonances at key speeds may all contribute to dynamic eccentricity.

Vibration Faults
Induction motors naturally experience vibrations, which are brought on by the motors' mechanical components oscillating. The external system that is connected to the machine shaft reflects these oscillations. As a result, a machine-related frequency spectrum that is exclusive to a healthy motor is produced. Every motor malfunction modifies the spectrum's frequency component. To identify and diagnose faults, this may be compared with the reference spectrum.

Fault Diagnosis

An induction motor's supply current spectrum may be examined to identify any issues that may arise. Only the forward spinning magnetic field will revolve at synchronous speed in a healthy motor; the backward rotating field will not exist. Any failure will produce in a backward spinning field in the air gap, which will alter the stator current spectrum. Table 1 summarizes the different frequency components that were added to the supply current spectrum as a result of failures [45]. The associated motor problems may be identified by keeping an eye on the different frequencies listed in Table 1. However, it has been noted [46–47] that these frequency components cannot be regarded as precise indicators of the occurrence of motor faults because they can be found in the spectrum of even healthy motors due to inevitable manufacturing symmetries, misalignment, etc. Over the years, numerous methods [48–49] have been proposed and developed that offer a good measure of the occurrence of faults in induction motors.
Table 1. Frequency Components of Induction Motor Faults

Faults	**Frequency**

Bearing Fault	$f_{cbf} = f_s \pm n f_{rc}$ $f_{rc} = \frac{N_b f_s}{2}\left(1 - \frac{D_b}{D_p}\cos\beta\right)$
Rotor Fault	$f_{cbrf} = f_s \pm n\left(\frac{1-s}{p}\right) f_s$
Eccentricity	$f_{ce} = f_s \pm nR \pm O_{re}\left(\frac{1-s}{P}\right) \pm O_{smh}$

where,

f_{cbf} = components generated by bearing faults f_s = supply frequency
n = 1,2,3… [Integral values]
f_{rc} = characteristics race frequencies N_b = number of bearing balls
D_b = ball diameter
D_p = bearing pitch diameter
= contact angle of the ball on the races
f_{cbrf} = components generated by broken rotor faults P = number of pole-pairs
s = per-unit slip
f_{ce} = components associated with eccentricity O_{re} = rotating eccentricity order
O_{smh} = stator MMF harmonic order R_s = number of rotor slots

Detection of Bearing Faults

Vibration Spectrum Analysis

High frequency components of vibration are produced by the forces acting on the rolling element bearing in electrical machines. These high frequency components are mostly caused by friction under normal circumstances, but in the event of a bearing malfunction, shock pulses may also be detected as a result of lubricating layer cracks between the friction surfaces. This technique uses a piezoelectric accelerometer to analyze the vibration spectrum of an induction machine by extracting the frequency domain representation from a time domain signal using the Fast Fourier Transform.

For example, a 0.75 kW induction motor with a 6202 ball bearing type and N = 8 balls is used for testing [50]. Both the motor with a damaged bearing and the healthy motor's harmonic vibration spectrum are examined separately. The vibration is seen in Figures 4(a)

and 4(b).

amplitudes for the motor with a healthy bearing and one with a damaged bearing, respectively, at the frequencies f1=100Hz, f2=152Hz, rotational frequency f=fr = 50Hz, and sideband 150-300Hz. A malfunctioning motor has a larger vibration amplitude than a functional motor.

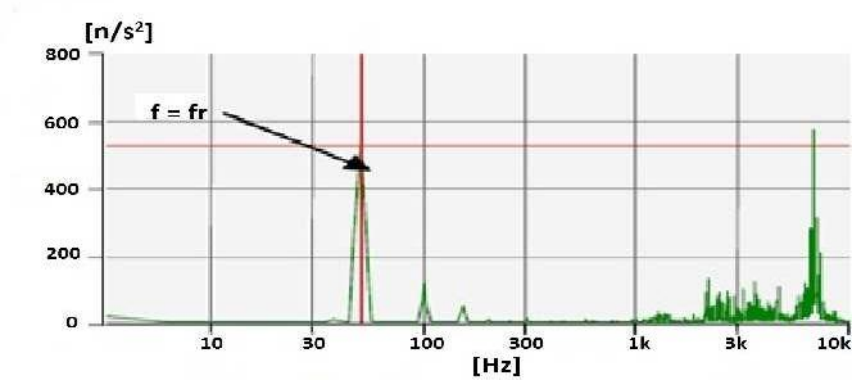


Fig. 4(a). Harmonic Vibration Spectra of Induction Motor with Good Bearing

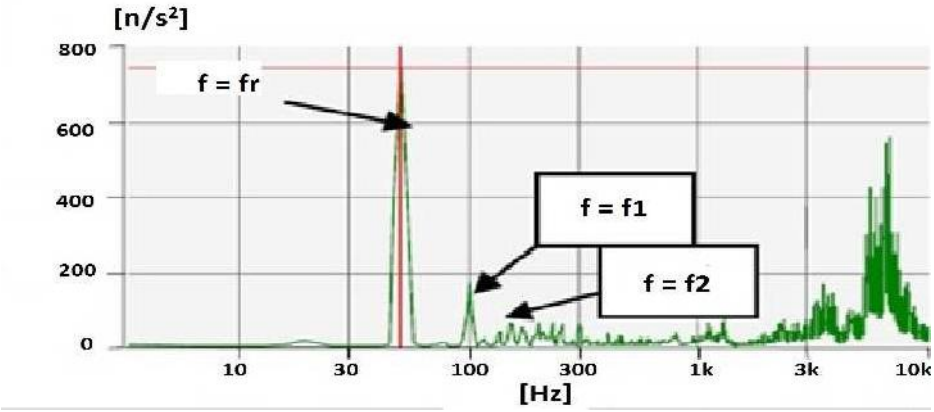


Fig. 4(b). Harmonic Vibration Spectra of Induction Motor with Bad Bearing

Dynamic Model to Simulate Bearing Faults and Analysis of Experimental Observation:

A winding function technique is used to simulate an induction motor with mixed eccentricities caused by inner race faults, and a dynamic simulation of a motor operating with bearing inner race faults is provided. Vibrations from trials on a motor with a defective bearing are contrasted with a spectrum analysis of electromagnetic torque produced by the simulated motor [51]. The power spectral density and frequency domain analysis of the vibration signal are detailed in Figures 5(a) and 5(b). After then, the spectrum magnitude is

standardized to have a 0.2 Hz bandwidth. This means that the power spectral density's magnitude leaks out to adjacent frequency bins at + 0.2 Hz from the faulty frequency for any fault frequency.

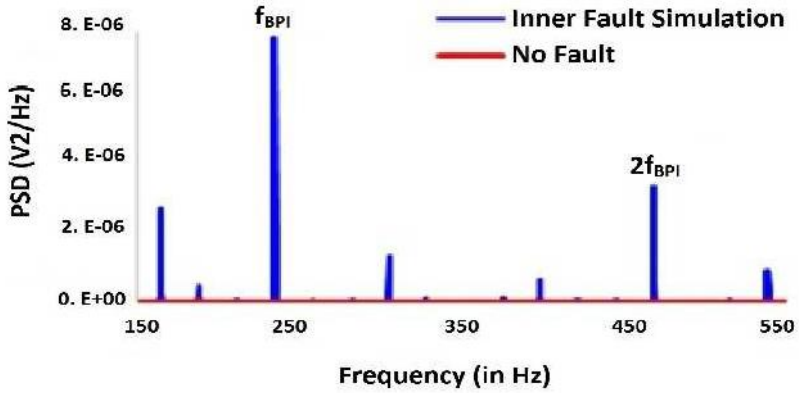


Fig.5(a). Frequency Spectrum of Electromagnetic Torque of Dynamic Simulation Motor with Bearing Fault

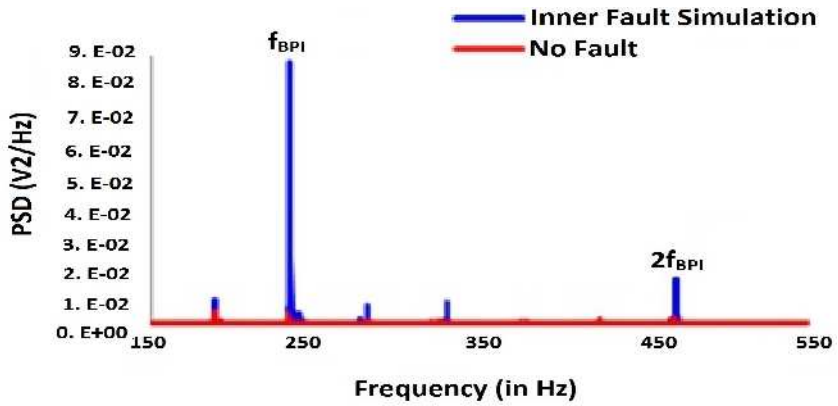


Fig.5(b). Characteristic Frequencies in the Spectral Analysis of Vibration of Induction Motor with Inner Race Bearing Fault

Detection of Stator Faults
Using Park Vector Approach and Complex Wavelets

The Park vector transformation method may be used to investigate how stator defect affects machine current. Park's vector is based on the location of the instantaneous spatial vector sum of the three phase stator currents. A three-phase induction motor often doesn't need a connection to the neutral. The connection to the three-phase mains is the only thing involved. Therefore, there is no homopolar current in the mains current.

Park's Transform may be used to create a two-dimensional depiction of an induction motor's three-phase current. The Park's vector components (ID, IQ) as a function of mains phase

variables (Ia, Ib, Ic) are:

$$I_D = \sqrt{\frac{2}{3}} I_a - \frac{1}{\sqrt{6}} I_b - \frac{1}{\sqrt{6}} I_c$$

$$I_Q = \frac{1}{\sqrt{2}} I_b - \frac{1}{\sqrt{2}} I_c$$

A circle is mapped by this.The center of this circle is located at the coordinates' origin (0, 0). Because stator winding problems deform this region, fault detection is made simple. In addition to simplifying analysis and computations, Park's Transform outperforms conventional techniques in terms of economy, particularly for small and medium-sized motors. Additionally, it may identify the problems without needing access to the motor.

A three-phase, four-pole induction motor model with 36 stator slots and 55 spins per slot is simulated in order to examine the suggested method [52]. Park's Transform is used to determine the Park vector currents once the three-phase supply currents are measured. Fig. 6(a) shows the Park vector of the motor current when there is no stator defect. The Park vector of the motor current in the event of a stator defect is shown in Fig. 6(b). A healthy motor's current Park's vector is a circle, but depending on the degree of defect, the form changes to an ellipse for a malfunctioning motor. Finally, complex wavelets are used to examine simulation and experimental data.

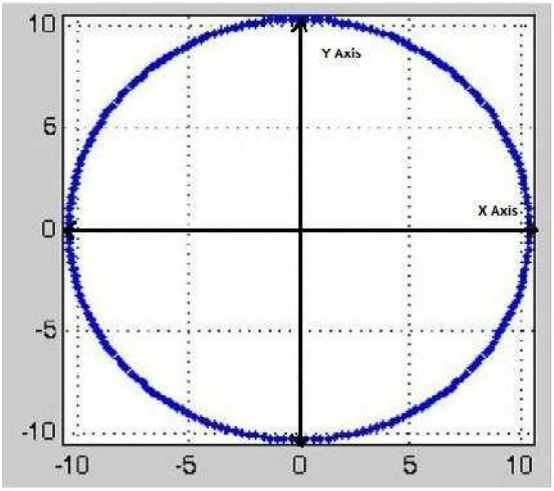


Fig.6(a). Motor Current’s Park’s Vector Representation at Healthy Case

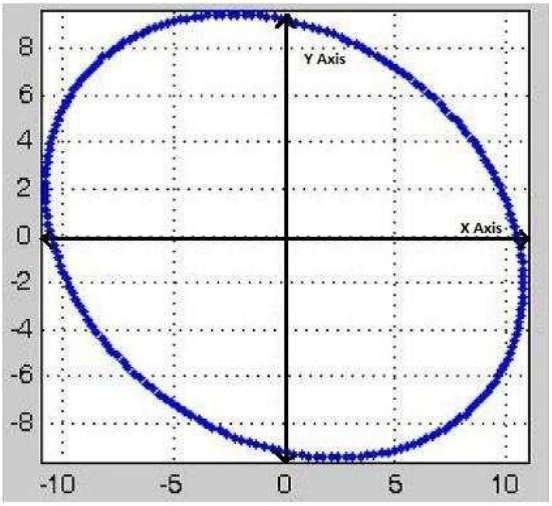


Fig.6(b). Motor Current's Park's Vector Representation at Faulty Case

Detection of Rotor Faults and Eccentricity

Motor Current Signature Analysis (MCSA)

MCSA analyzes current harmonics in the stator current [53–59]. Due to a failure, fresh spinning flux components are responsible for these harmonics. It is based on signal processing methods such as FFT and requires just one current sensor [60]. Fig. 7 depicts the apparatus used to measure motor current. FFT is used to the stator current in order to acquire data. After FFT, the data is normalized as a function of the first harmonic amplitude and examined. Figures 8(a) and 8(b) show FFT with rotor bars in their original state and with three fractured rotor bars, respectively.

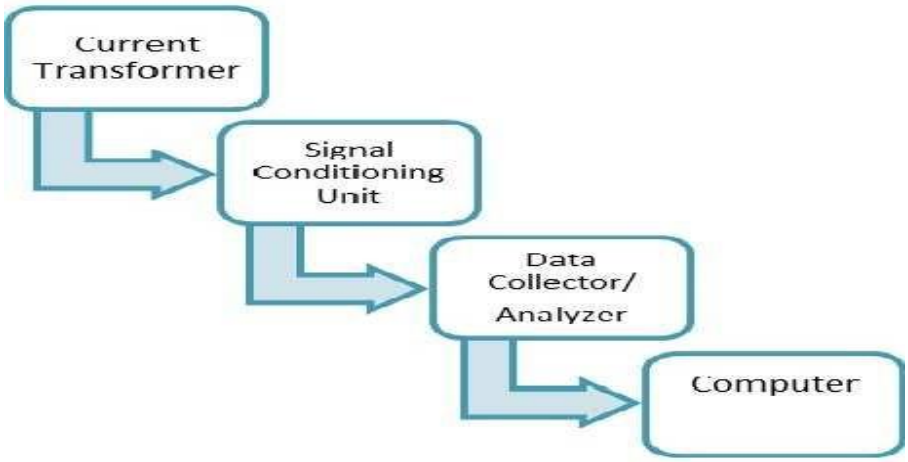


Fig.7 Set-Up for Measuring Motor Current

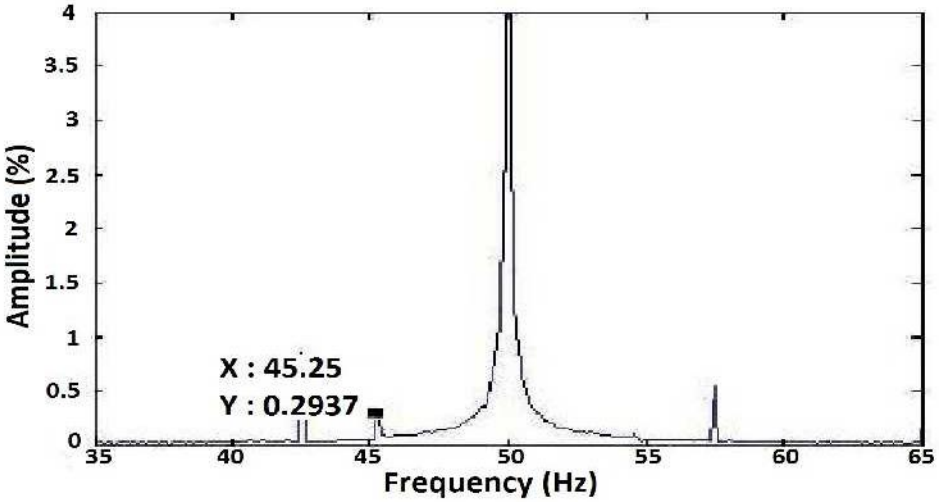


Fig. 8(a) FFT with initial condition for broken bars

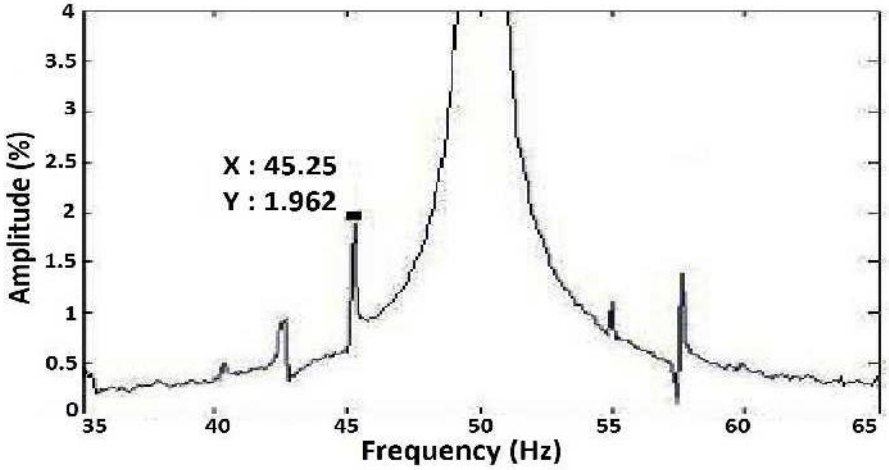


Fig .8 (b) FFT with 3 broken bars

Table 2 indicates the percentage amplitude for harmonics with different number of broken rotor bars. Evidently, the harmonic contents increase with increase in fault level i.e. rise of count of broken rotor bars.

Table 2. Results of Broken Bar Faults

Frequency(Hz)	Amplitude%	No. of Broken Bars
45.25	0.2937	0
45.25	1.028	1
45.25	1.83	2
45.25	1.962	3

Similarly, eccentricity also causes a change in the FFT of induction motor. Fig. 9(a) and Fig. 9(b) illustrate the FFT with initial condition of rotor bars and with 87.3% eccentricity respectively.

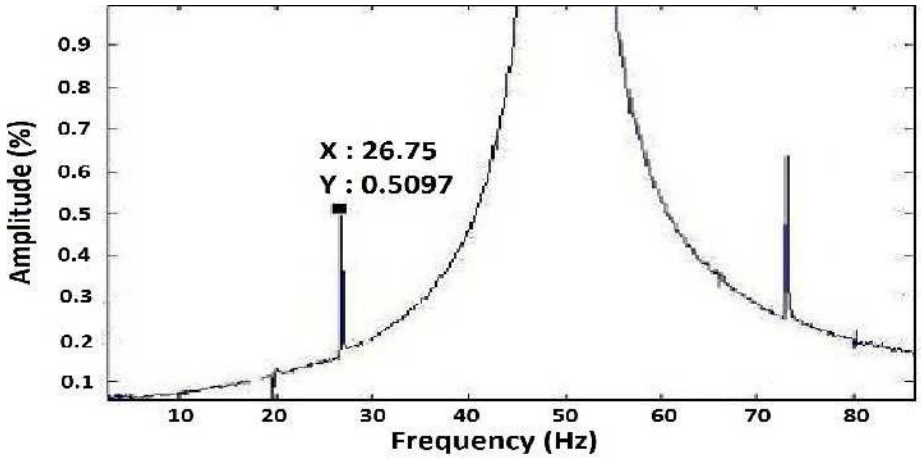


Fig. 9 (a) FFT with initial condition of Rotor's eccentricity

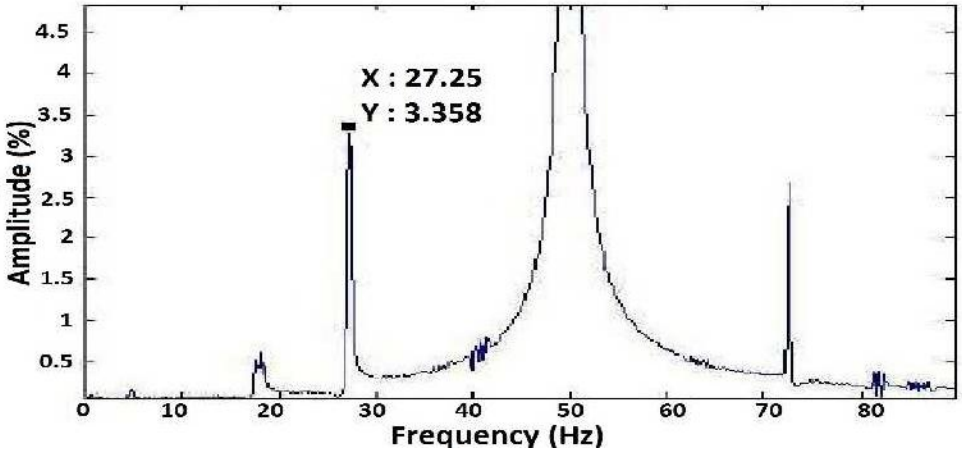


Fig. 9 (b) FFT with 87.3% of Rotor's eccentricity

Table 3 specifies the percentage amplitude for harmonics with varying levels of eccentricity. Markedly, the harmonic contents increase with increase in fault level i.e. increase of eccentricity.

Table 3. Results of eccentricity

Eccentricity (%)	**Amplitude%**
0	0.59
44.5	1.96
87.3	4.94

Intelligent Techniques

For the purpose of monitoring the status of induction motors, a number of intelligent methods have been thoroughly addressed, including fuzzy logic systems [61–63], artificial neural networks [64–66], neuro-fuzzy systems [67–69], etc. Any diagnostic method based on artificial intelligence (AI) typically consists of three main steps: i) signature extraction; ii) fault identification; and iii) fault severity estimate. A schematic of neural networks for an induction motor's condition monitoring is shown in Fig. 10 [70].

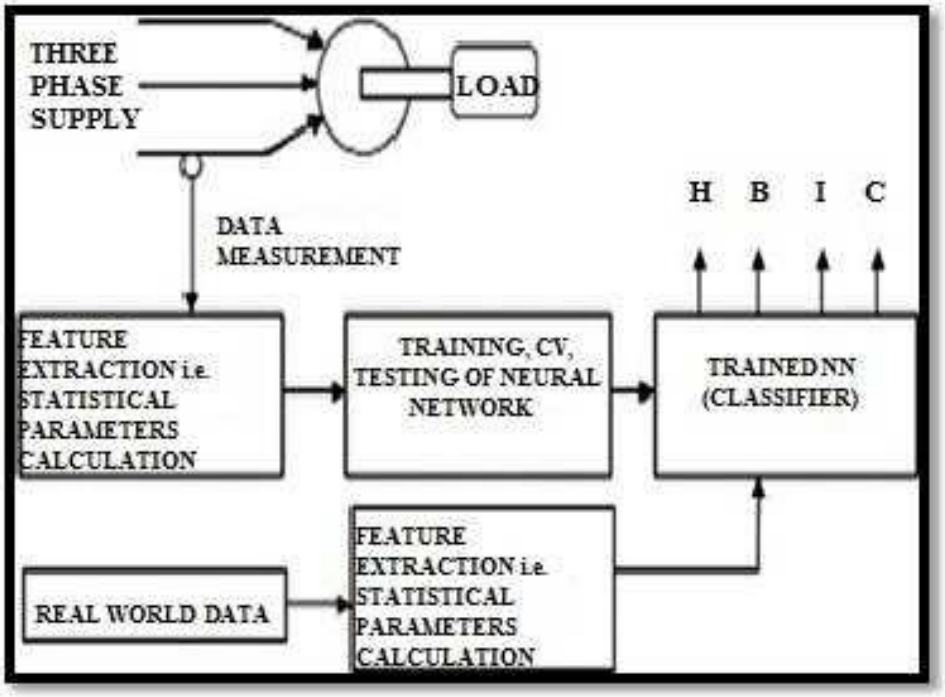


Fig. 10 Neural Network Schematic for Condition Monitoring of Induction Motor

Apart from these techniques, some other methods for the incipient fault detection of induction motor have found a mention in other literature [71-77]. Table 4 presents an elaborate comparison of several fault detection techniques and the faults generally detected by them.

Table 4. Comparison of various fault detection techniques

Fault Detection Techniques	**Detected Faults**
MCSA	Bearing, Rotor, Stator and Vibration Faults
Park's Transform	Bearing and Stator Faults
Artificial Neural Networks	Bearing and Rotor Faults
Wavelet Analysis	Bearing, Rotor, Stator and Vibration Faults
Finite Element Method	Rotor, Stator and Vibration Faults
Vibration Testing and Analysis	Bearing and Vibration Faults
Concordia Transform	Bearing Faults
External Magnetic Field Analysis	Rotor Faults
Multiple Reference Frames Theory	Eccentricity
Power Decomposition Technique	Stator Faults

KU Transformation Theory	Stator Faults
Zero Crossing Time Method	Stator Faults
Modal Analysis Method	Vibration Faults

Scope Of Future Work

Rules derived from heuristic knowledge and the connection weight of a supervised neural network may be used by expert systems to diagnose faults. Artificial neural networks and specialized expertise might improve the diagnostic monitoring system.

Additionally, a database of vibration harmonics for different sizes and design standards of three-phase induction motors may be developed by theoretical and practical research. The conventional vibration standard, which relies on the RMS velocity of vibration rather than harmonic amplitude, may be replaced with a new one using this database.

Conclusion

This essay aims to provide an overview of current advancements in the diagnosis and prognosis of induction motor faults. In this study, a variety of methods, models, and algorithms have been examined, and the applicability of a certain method for a particular fault diagnosis has been emphasized.

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