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Fault Diagnosis of an Induction Motor Using Motor Current Signature Analysis

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Abstract

An induction machine is a highly non-liner system, that possesses a great challenge because of its fault diagnosis due to processing of large and complex data. The faults in induction machines lead to excessive downtime, this results in huge losses in terms of maintenance and production. In this paper, the technique called Motor Current Signature Analysis (MCSA), which is based on the current monitoring technique, is applied. It uses the current spectrum of the machine for loading characteristic fault frequencies. Signal processing technique for condition monitoring is used for the measurement of fault detection. Therefore, the effects of various faults associated with current spectrum are investigated through experimental results. The experiment is performed on 3-phase, 0.5 hp, 4 poles and 50Hz motor. The scan rate is 0.2 Mega-samples/second. The Virtual Instrument (VI) is used to obtain the power spectrum with the help of programming in LabVIEW software. Experiments are conducted according to the severity with respect to short winding fault against load conditions and for short circuited winding at 7.7% and 23%. The hardware and simulation results are compared and proposed in this paper.

Keywords: Fault Diagnosis, Motor Current Signature Analysis (MCSA), Induction Motor, LabVIEW

INTRODUCTION

An induction machine is highly non-linear system that poses a great challenge for fault diagnosis due to the processing of large and complex data. The fault in an induction machine can lead to excessive downtime, which leads to huge losses in terms of maintenance and production which is critical in industries. Stator inter-turn faults are one of the most common faults occurring in induction motors. Early detection of inter-turn short circuit is important to reduce repair costs [1]. Fault detection analysis using different methods are not always possible because this requires thorough and exact motor model parameters. There are 6 various types of faults which occur in Induction motors. They are:

a. Broken rotor bar fault, b. Stator winding fault, c. Air gap eccentricity fault, d. Gear box fault, e. Bearing failure, and f. Load fault.

Most of the faults in motor are dominated by bearing failure and stator coils. As shown in fig. 1, the major portion of failure statistics happens in the bearing fault which is of 41% and the second major fault is in field of stator winding fault which secures 37% of the overall area. The other two known types of faults consume 12% and 10% in other types of faults and broken rotor bar fault, respectively.

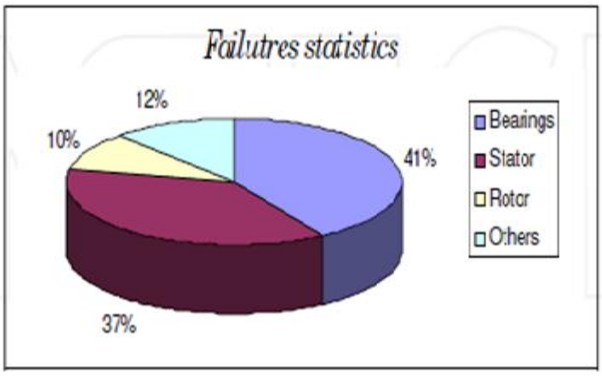

Figure 1: Percentage of various faults

A technique called Motor Current Signature Analysis (MCSA) [2] is based on current monitoring of induction motor; therefore, it is not very expensive. It uses current spectrum of the motor for locating characteristic fault frequencies. When a fault is present, the frequency spectrum of the line current becomes different from healthy motor. Such a fault modulates the air-gap and produces rotating frequency harmonics in the self and mutual inductances of the machine. It depends upon locating specific harmonic component in the line current. Therefore, it offers significant implementation and economic benefits. In this paper, the signal processing technique is used for condition monitoring and fault detection of an induction motors. The signal processing technique used here has advantages that are not computationally expensive, and these are simple to implement. Therefore, fault detection based on the signal processing technique is suitable for an automated on-line condition monitoring system. Usually, signal processing techniques analyses and compares the magnitude of the fault frequency components, where the magnitude tends to increase as the severity of the fault increases.

The proposed methods in this paper allows continuous real time tracking operation under continuous and variable loaded conditions. FFT the signal processing techniques is used in present work for detection of Stator Winding faults of an induction motor. Signal processing technique has their limitations. The effects of various faults on current spectrum of an induction motor are investigated through experiments. This paper is organized as sections which gives an elaborative approach of introduction. Section II gives general idea of main faults in electrical machines. Section III is the section of signal processing technique. Section IV shows the experimental setup and simulation results. Section V elaborates observations and discussions from the simulation results. Section VI is conclusion and future scope.

MAIN FAULTS IN ELECTRICAL MACHINES

An induction motor is defined as an asynchronous machine that comprises a magnetic circuit which interlinks with two electric circuits rotating with respect to each other and in which power is transferred from one circuit to another by electromagnetic induction [1]. It is an electromechanical energy conversion device in which the energy converts from electric to mechanical form [5]. The energy conversion depends upon the existence in nature of phenomena interrelating magnetic and electric fields and mechanical force and motion.

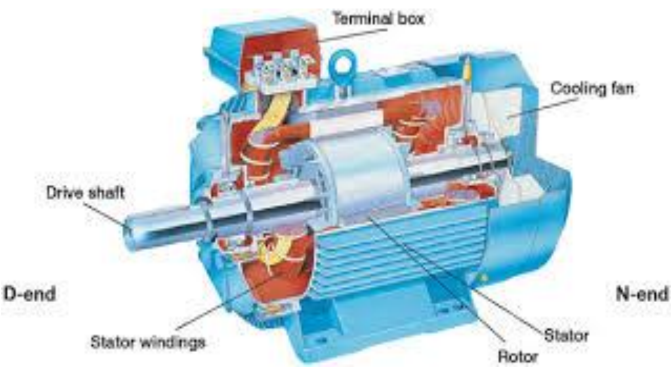

Figure 2. General diagram of induction motor

Broken Rotor Bar Faults

Usually, lower rating machines are manufactured by die casting techniques whereas high ratings machines are manufactured with copper rotor bar. Several related technological problems can rise due to manufacturing of rotors by die casting techniques. It has been found that squirrel cage induction motors show asymmetries in the rotor due to technological difficulties or melting of bars and end rings. However, failures may also result in rotors because of so many other reasons. There are several main reasons of rotor faults.

- During the brazing process in manufacture, non-uniform metallurgical stresses may be built into cage assembly and these can also lead to failure during operation.
- A rotor bar is unable to move longitudinally in the slot it occupies, when thermal stresses are imposed upon it during starting of machine.
- Heavy end ring can result in large centrifugal force, which can cause dangerous stress on the bars.

Because of the above reasons, rotor bar may be damaged and simultaneously unbalance rotor situation may occur. Rotor cage asymmetry results in the asymmetrical distribution of the rotor currents. Due to this, damage of the one rotor bar can cause the damage of surrounding bar and thus damage can spread, leading to multiple bar fractures.

Stator Winding Fault

According to the survey, 37% of induction motor failures are related to the stator winding insulation. Moreover, it is generally believed that a large portion of stator winding-related failures are initiated by insulation failures in several turns of a stator coil within one phase. This type of fault is referred as a “stator turn fault”. A stator turn fault in a symmetrical three-phase AC machine causes a large circulating current to flow and subsequently generates excessive heat in the shorted turn. If the heat which is proportional to the square of the circulating current exceeds the limiting value the complete motor failure may occur. However, the worst consequence of a stator turn fault may be a serious accident involving loss of human life.

The organic materials used for insulation in electric machines are subjected to deterioration from a combination of thermal overloading and cycling, transient voltage stresses on the insulating material, mechanical stresses, and contaminations. Among the possible causes, thermal stresses are the main reason for the degradation of the stator winding insulation. Regardless of the causes, stator winding-related failures can be divided into the five groups:

a. Turn-to-turn,
b. Coil-to-coil,
c. Line-to-line,
d. Line-to-ground, and
e. Open-circuit faults.

Air Gap Eccentricity Fault

Air gap eccentricity is common rotor fault of induction machines. This fault produces the problems of vibration and noise. In a healthy machine, the rotor is centre aligned with the stator bore, and the rotor’s centre of rotation is the same as the geometric centre of the stator bore. When the rotor is not centre aligned, the unbalanced radial forces (unbalanced magnetic pull or UMP) can cause a stator-to-rotor rub, which can result in damage to the stator and the rotor.

Bearing Fault

Bearings are single largest cause of machine failures. According to some statistical data, bearing fault account for over 41% of all motor failures. A continued stress on the bearings causes fatigue failures, usually at the inner or outer races of the bearings. Small pieces break loose from the bearing, called flaking or spalling. These failures result in rough running of the bearings that generates detectable vibrations and increased noise levels. This process is helped by other external sources, including contamination, corrosion, improper lubrication, improper installation, and brine ling. The shaft voltages and currents are also sources for bearing failures. These shaft voltages and currents result from flux disturbances such as rotor eccentricities. High bearing temperature is another reason for bearing failure. Bearing temperature should not exceed certain levels at rated condition.

Load Fault

In some applications such as aircrafts, the reliability of gears may be critical in safeguarding human lives. For this reason, the detection of load faults (especially related to gears) has been an important research area in mechanical engineering for some time. Motors are often coupled to mechanical loads and gears. Several faults can occur in this mechanical arrangement. Examples of such faults are coupling misalignments and faulty gear systems that couple a load to the motor.

SIGNAL PROCESSING TECHNIQUES

The Discrete Fourier Transform (DFT) is the most straight mathematical procedure for determining frequency content of a time domain sequence, it's terribly inefficient. As the number of points in the DFT is creased to hundreds, or thousands, the amount of necessary number crunching becomes excessive. In 1965 a paper was published by Cooley and Tukey describing a very efficient algorithm to implement DFT. That modified algorithm is now known as the Fast Fourier Transform [6]. FFT is simply a computationally efficient way to calculate the DFT. By making use of periodicities in the signs that are multiplied to do the transforms, the FFT greatly reduce the amount of calculation required.

The Power spectrum is computed from the basic FFT function. The power spectrum shows power as the mean squared amplitude at each frequency line. The FFT in LabVIEW returns a two-sided spectrum in complex form (real and imaginary parts), which must scale and convert to polar form to obtain magnitude and phase. The frequency axis is identical to that of the two-sided power spectrum. The amplitude of the FFT is related to the number of points in the time-domain signal. There is a relationship between the mechanical vibration of a machine and the magnitude of the stator current component at the corresponding harmonics. For increased mechanical vibrations, the magnitude of the corresponding stator current harmonic components also increases. This is because the mechanical vibration modulates the air gap at that particular frequency. These frequency components then show up in the stator inductance, and finally in the stator current. As the flux density in the air gap is defined as the product of the winding magneto-motive force (MMF) and the air-gap permeance, variations in either of these will cause anomalies in the flux distribution. The changes in the winding MMF mainly depend on the winding distribution.

On the other hand, the air-gap permeance depends on numerous effects including stator slots, out-of-round rotors, air-gap eccentricities caused by mechanical unbalance and misalignment, and mechanical shaft vibrations caused by bearing or load faults. MCSA detects changes in a machine's permeance by examining the current signals. It uses the current spectrum of the machine for locating characteristic fault frequencies. The spectrum may be obtained using a Fast Fourier Transformation (FFT) that is performed on the signal under analysis. The fault frequencies that occur in the motor current spectra are unique for different motor faults. This method is the most commonly used method in the detection of common faults of induction motors. Some of the benefits of MCSA include:

a. Non-intrusive detection technique: With the technological advances in current- measuring devices, inexpensive and easy- to-use clamp-on probes are more affordable and convenient to use for sampling current without having to disconnect the electrical circuit or to disassemble the equipment.

b. Remote sensing capability: Current sensors can be placed anywhere on the electrical supply line without jeopardizing the signal strength and performance.

c. Safe to operate: Since there is no physical contact between the current sensor and the motor-driven equipment, this type of monitoring technique is particularly attractive to applications where safety is of major concern.

MCSA is the online analysis of current to detect problems in a three-phase induction motor drive while it is still operational and in service. An idealized current spectrum is shown in Figure 3 and a basic MCSA instrumentation system in Figure 4.

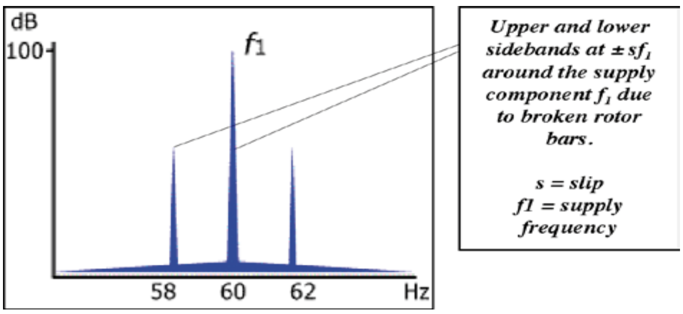

Figure 3. An idealized current spectrum

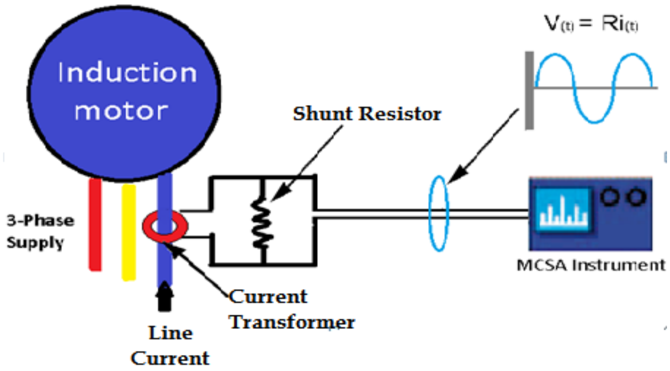

Figure 4. Basic MCSA Instrumentation Diagram

EXPERIMENTAL SETUP AND SIMULATION RESULTS

In order to diagnose the fault of induction motor with high accuracy, a test setup was arranged as shown in Figure 5. It consists of three phase induction motor coupled with belt pulley, transformer, NI myDAQ, Dell Personnel Computer with software LabVIEW. The rated data of the tested three-phase squirrel cage induction machine were: 0.5 hp, 415V, 1.04 A and 1408(FL) r/min. The parameters of experimental motor are given in Table 1. LabVIEW software is used to analyze the signals. It is easy to take any measurement with NI LabVIEW. The measurements can be automated from several devices and data can be analyzed spontaneously with this software.

Figure 5. Experimental Setup for Stator Winding Short Circuit Fault Detection

Data acquisition device myDAQ are used to acquire the current samples from the motor under load. This is a high-speed multifunction data acquisition (DAQ) device which can measure the signal with superior accuracy at fast sampling rates and technology for improved measurement accuracy. It has an onboard OPA1642 amplifier designed for fast settling times at high scanning rates. This device has 4 analog inputs and 8 digital I/O lines. Figure 5 shows the NI myDAQ. Experimental setup is further divided into hardware and software.

The hardware mainly includes Induction motor with specification mentioned in table 1, other secondary part and NI-My DAQ device. Other secondary parts are Current Transformer (with turns ratio 5:1), resistor: as I to V converter 10Ω, loading arrangement with belt and pulley, a switch to create fault in motor, multi-meter, ammeter (0 – 2A), two pole selector Switch to create fault in stator winding.

Table 1. Parameters of Experimental Motor

Parameter	**Data**
Power	0.5 Hp
Frequency	50 Hz
No. of phases	3
Speed	1490 rpm
Volt	415V
No. of pole pair	2
No. of stator slots	24

The software mainly includes the Data Acquisition Parameters and LabVIEW programming. Digital Signal Processing is done in FFT Analysis.

Side Band Frequency Determination

Side band frequency is nothing but fault frequency the frequency at which fault occurs can be calculated as follows:

$$\text{Slip} = \frac{\text{Synchronous Speed} - \text{Rated Speed}}{\text{Synchronous Speed}} \times 100$$

$$f_{st} = f\left[k \pm \frac{n}{p}(1-s)\right]$$

Where, p = pole pairs

s = rotor slip

k = 1,3,5...

f = fundamental frequency(Hz)

f_{st} = short circuit related frequency(Hz)

n = integer 1,2,3…

Table 2. Slip and Sideband Frequency Determination

Load condition	**Speed (rpm)**	**Slip**	k=1	
			LSB	MSB
No load	1490	0.06	26 Hz	75.5Hz
Full load	1408	0.06	23Hz	76.5Hz

Table 2, shows the experimental fault frequency at various load conditions. The difference between no load condition and full load condition is that the speed is reduced with increase in load with lower LSB and higher MSB values.

Simulation Results

Table 3: Different Short Circuit Condition

Experiments	Severity of short winding fault	Load condition
1	0% shortened	No load
2	7.7% shortened	No load
3	23%	No load
4	0% shortened	Full load
5	7.7% shortened	Full load
6	23% shortened	Full load

At 7.7% and 23%, during the test, the motor was coupled with pulley and belt. The Figure 6 shows the power spectrum of healthy motor under no load condition. The motor was operating at 1.02 Amp, corresponding to no load. As observed from Fig. 6, the spectrum is completely free of faulted current components around main supply frequency. The motor thus shows no sign of stator winding faults. The experimental results for 7.7 % and 23% short circuit of winding are given below:

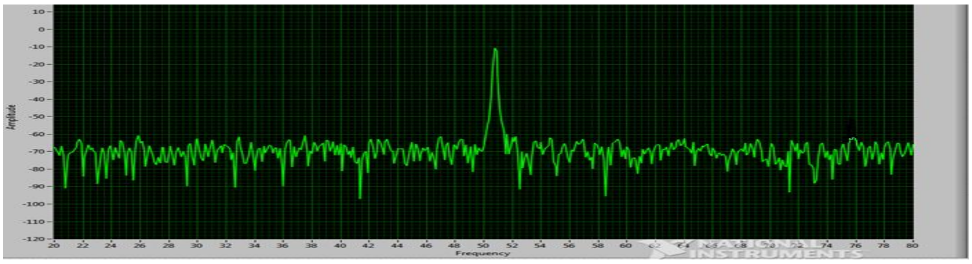

Figure 6. Power spectrum of healthy motor under no load condition

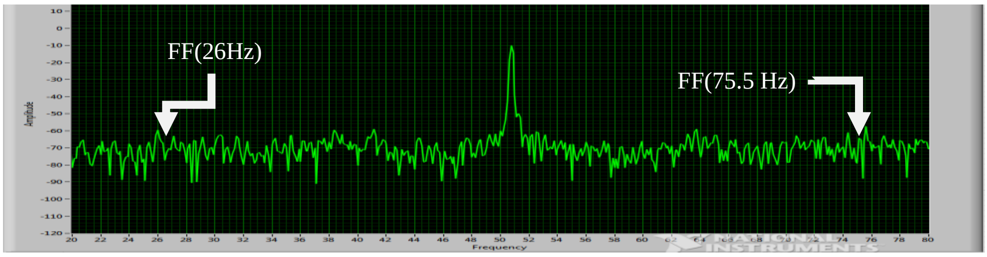

Figure 7. Power spectrum of healthy motor with 7.5 % shorten end under no load condition

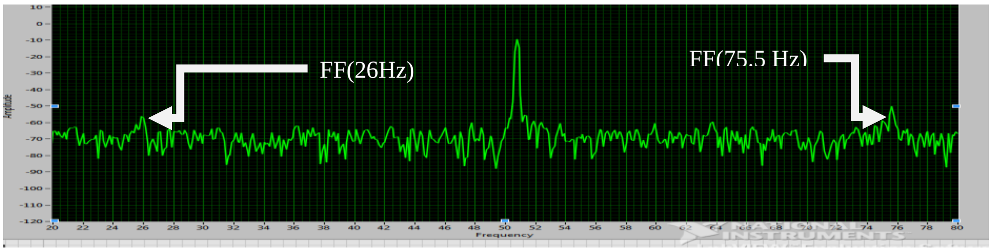

Figure 8. Power spectrum of healthy motor with 23 % shortened under no load condition

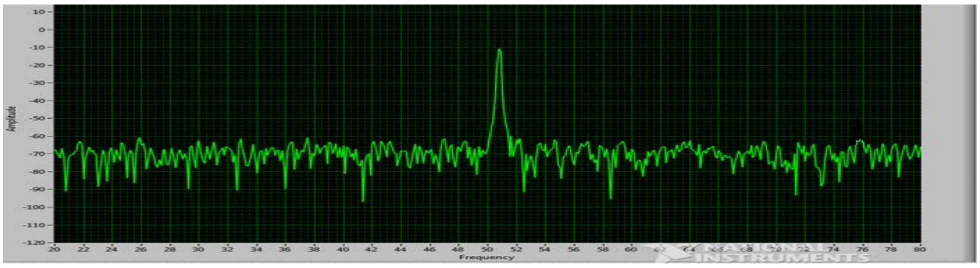

Figure 9. Power spectrum of healthy motor under full load condition

Figure 10. Power spectrum of healthy motor with 7.5 % shortened under full load condition

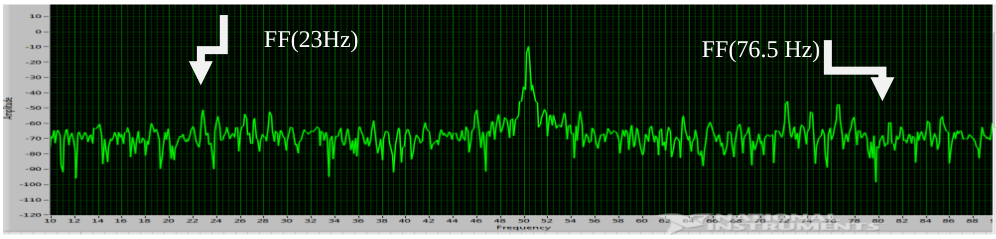

Figure 11. Power spectrum of healthy motor with 23 % shortened under full load condition

OBSERVATION AND DISCUSSION

a. 7.7 % Short-circuited winding

The power spectrum of faulty motor with 7.5 % short circuit at no load condition is shown in figure 6. The fault frequencies are appearing at 26 Hz and 75.5 Hz. At full load, fault frequencies appear at 23 Hz and 76.5 Hz. It is observed from Figure 7 that, at no load magnitude of fault frequency is -60dB whereas at full load magnitude is -58 dB. It indicates that magnitude of fault frequency increases with increases in load.

b. 23% Short-circuited winding

The power spectrum of induction motor is plotted for no load and full load operating conditions with increased severity of 23% fault. The Figure 8 shows the power spectrum of faulty motor with 23% short circuit of winding at no load. The fault frequencies appear at 26Hz and 75.5Hz. It justifies the calculated and experimental results. The magnitude of fault frequencies is found in between -56 dB to -50dB for LSB and USB. Magnitude of fault frequencies has been increased when compared with magnitude of 7.7% severity of fault. The magnitude of fault frequency increases with increases in severity of fault. Increase in magnitude of current component is undesirable aspect for the performance of induction machine. The same outcome has been observed for full load condition as shown in Figure 11 The fault frequencies appear at 23 Hz and 76.5 Hz which is also a calculated value at full load condition. However, the magnitudes of these fault frequencies have been significantly increased due to its increased loading condition and severity of fault.

Table 4: Experimental Results

Fig no.	Short circuited stator winding	Load condition	Fault frequencies				Observation
			Lower side band		Upper side band		
			FF(Hz)	Mag.(dB)	FF(Hz)	Mag.(dB)	
8.1	0%	No Load	26	-60	75.5	-60	Visible
8.2	7.5%	No Load	26	-60	75.5	-58	Visible
8.3	23%	No Load	26	-56	75.5	-50	Visible
8.4	0%	Full Load	23	-67	76.5	-66	Visible
8.5	7.5%	Full Load	23	-54	76.5	-46	Visible
8.6	23%	Full Load	23	-50	76.5	-48	Visible

The investigations can be expanded by introducing multiple stator and rotor fault types into a motor. For large size motors, new challenges may exist for current based fault detection. Therefore, proposed techniques may be applied for fault diagnosis of large size motors. Additional work is needed to investigate the applicability of other signal processing tools in characterizing the fault signature. There is a need to study the effects of electric drives because there may be a change in the current spectrum. The effects of non-stationary operations on the stator current need to be investigated for fault detection purposes.

OBSERVATIONS AND DISCUSSION

The following conclusions can be drawn from the observations of results obtained by the experiments:

a. If severity of faults is increased, the magnitude of fault frequency increases. Hence, short winding fault with high severity can be easily identified.

b. It is easy to diagnose the short winding fault at high load conditions because magnitude of fault frequencies increases with increase of load. The frequencies with high magnitude can be easily identified.

c. The multi-resolution analysis is best suited for detection of short winding fault at non- stationary load conditions. Experiments were performed for both healthy and faulty motor conditions under varying load conditions and then results were compared to make conclusions.

d. The harmonic variation is seen in the expected bands for this kind of fault in the range of low frequencies from 25 Hz to 200 Hz. Hence, results show the significant variations in detail which corresponds to bandwidth where faulty frequency appears. Based on the results obtained from the experiments, it can be concluded that, multi-resolution analysis can be comparatively better technique to diagnose short circuit winding faults of the induction motor.

e. The implemented and tested method showed the efficiency in fault diagnosis and condition monitoring of induction motor. The results obtained has a great degree of reliability, which enables the proposed methods as monitoring tools for diagnosis of short winding fault of similar motors.

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