Induction Motor Fault Detection and Diagnosis by Vibration Analysis using MEMS Accelerometer

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***Abstract*—Three phase induction motors have been widely adopted, mainly because of their low price, ruggedness, simplicity of control, and reliability. The induction motor is considered as a robust and fault tolerant machine and is a popular choice in industrial drives. The purpose of this work is to demonstrate the importance of vibration measurements in fault detection and diagnosis of induction motors. The vibration analysis demands appropriate vibration transducer. MEMS based accelerometers are emerging as the alternate method of sensing the vibrations in a rotating machine. With the advent of MEMS technology there is a remarkable reduction in size, power consumption and cost of MEMS accelerometers compared to conventional accelerometer. The primary objective of the work is to detect and diagnose induction motor faults, caused due to electrical or mechanical origin by vibration analysis. Fault causes change in mechanical and electrical forces acting on the machine. This paper gives a justification for the change in machine vibration due to the excitation of voltage harmonics; this in turn will help in electrical fault detection in induction motor. Also, presents a method for detecting faults occurring due to mechanical origin such as mechanical looseness and misalignment in motor shaft coupled to brake drum with the help of MEMS accelerometer used as vibration sensor.**

Keywords—MEMS accelerometer, Vibration analysis, Vibration measurement, Electrical fault, Mechanical fault.

I. INTRODUCTION

In a wide variety of industrial applications, an increasing demand exists to improve the reliability and availability of electrical systems. Amongst all types of electric motors, induction motors are a frequent example due to their simplicity of construction, robustness and high efficiency. Moreover, induction motors may be supplied directly from a constant frequency sinusoidal power supply or by an ac variable frequency drive.

Electric motors are designed to work under variable loads, most commonly under periodic loads. Thus, all machines are prone to forced vibrations and hence dynamic stresses. In general rotating machinery is subjected to dynamic loads. Therefore, any change in the mechanical condition of the machine affects its dynamic conditions and thus the vibration behavior.

There are many mechanical and electrical forces present in electrical machines that can produce vibrations. Further these forces interact, making the identification of the root cause elusive. Vibration signatures are widely promoted as a useful tool for studying machine malfunctions. Early diagnosis of faults in electric machines is an extensively investigated field for maintenance cost and downtime savings. The induction motor is subjected to primary types of fault and secondary faults. The source of faults may be internal or external or due to environment. Internal faults are classified with reference to their origin i.e. electrical or mechanical. Similarly, external faults are classified with reference to their origin i.e. electrical, environmental or mechanical. All rotating equipment produces vibration. Even new or healthy machine generates some level of vibrations. Over entire service life of machines, component deformation and damage cause dynamic characteristics to change and eventually increase the level of the machine vibrations. The magnitude of vibration produced is primarily dependent on the magnitudes of the original forces on both mechanical response of the structures of the machine and its mountings. This response depends on frequency and mode of vibration that is excited.

A relatively large force may cause little vibration, if the response of the structure at the forcing frequency of the particular mode of vibration is small. Similarly, a relatively small force exciting a particular mode of vibration of some part of the structure at or near the resonant frequency may cause a considerable vibration. The vibration produced by an electrical machine may be reduced, either by reducing the magnitude of the original forces or by modifying the machine structure and its supports, so that the forces cause smaller response.

II. PROPOSED METHODOLOGY

The proposed method is for fault detection and diagnosis in induction motor which includes detection of faults occurring due to electrical and mechanical origin. The faults occurring due to mechanical origin are detected by mounting MEMS accelerometer. Justification is given for the change is machine vibration due to the excitation of voltage harmonics. This in turn will help in electrical fault detection in induction motor.

A. *Justification for the Effects of Voltage Harmonics on Motor Vibration*

Create electrical faults on the supply side of the three phase induction motor using PSCAD software. The electrical faults created in PSCAD software are interphase fault and phase to ground fault. Through simulation an attempt is made to justify how voltage harmonics created due to electrical faults effect the frequency components of motor vibration. Fig. 1 shows the various types of electrical faults in induction motor. Hence PSCAD/EMTDC software is found beneficial for creating fault and plotting the FFT spectrum for the purpose of analysis.

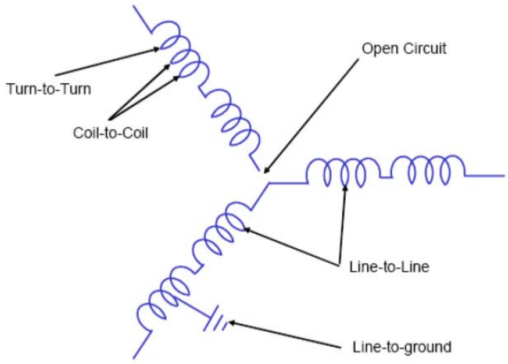

Fig. 1. Various types of electrical faults in Induction motor

Presence of fault causes change in mechanical and electrical forces that are acting in the machine. The degree of change depends upon the nature and intensity of fault. The change in machine vibrations is due to the excitation of some of the voltage harmonics. When the voltage supplied to induction motor is distorted then the voltage has harmonic voltage components. Harmonic voltage distortion at the motor terminals is translated into harmonic fluxes within the motor.

On other side, harmonics currents are introduced when line voltages applied to an induction motor include harmonics voltage components. The induction motor may be subjected to various types of electrical faults as stated before. The effect of these faults is distortion in the air-gap flux of the machine. The degree of distortion depends upon type and degree of faults and ultimately the induced vibration. Some of these harmonics have a dominant value in the vibration spectrum due to interaction of machine flux harmonics and the mechanical structure of the machine. Although the induced harmonics affects the whole frequency components of the vibration, only some components are subjected to change. These frequency components can be used to detect the presence of machine faults.

An induction motor connected to three phase supply is built using Power System Computer Aided Drawing (PSCAD) software for the purpose of analysis of electrical fault spectrum. The induction motor model is readily available in the PSCAD software, as per the name plate details the voltage, current, power, frequency and other required information has to be entered in the software. The name plate details of the induction motor model are as shown below:

Three Phase, delta connected, Squirrel cage induction motor

Rated Power: 3.4 Hp; Rated Voltage: 400V;

Rated Current: 5A; Frequency: 50Hz; Speed: 1440 rpm

Fig. 2 shows induction motor connected to three phase supply using PSCAD software. The motor faults are due to mechanical and electrical stresses. Mechanical stresses are caused by overloads and abrupt load changes. On the other hand, electrical stresses are usually associated with the power supply.

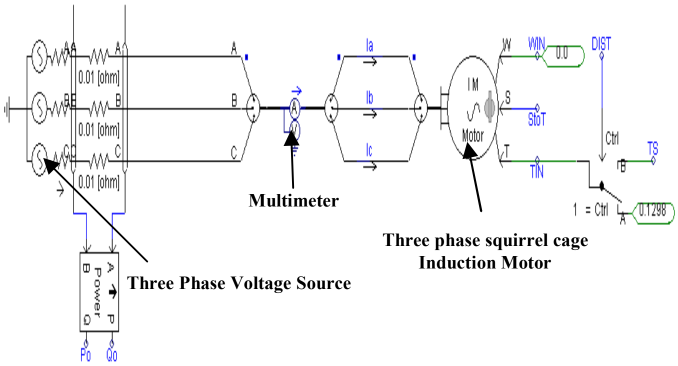

Fig. 2. Induction motor connected to power supply in PSCAD software

Induction motors can be energized from constant frequency sinusoidal power supplies or from adjustable speed ac drives. However, induction motors are more susceptible to fault when supplied by ac drives. This is due to the extra voltage stress on the stator windings, the high frequency stator current components, and the induced bearing currents, caused by ac drives. In addition, motor over voltages can occur because of the length of the cable connections between a motor and an ac drive. Such electrical stresses may produce stator winding short circuits and result in a complete motor failure.

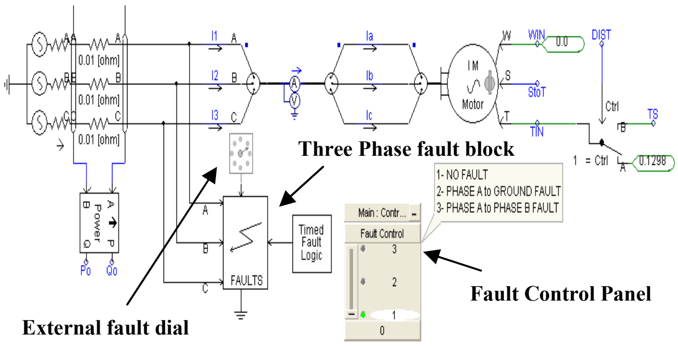

Fig. 3. Induction motor connected to power supply with three phase fault at the supply side in PSCAD software

Fig. 3 shows induction motor connected to power supply with three phase fault at the supply side. The three phase fault has external fault dial, there is also a timed fault logic block wherein the fault occurring time and fault clearing time can be entered. At present work the fault occurring time is given as 5second and the fault clearing time entered is very high for the purpose of analysis. As the fault clears, there will be changes in the FFT spectrum and the FFT spectrum obtained cannot be compared with the non faulty condition, because as the fault clears the system gets back to its normal operation, due to this reason the fault clearing time is, given very high so as to analyze and compare the fault spectrum. This makes comparison and analysis of the FFT spectrum between faulty and non-faulty condition easier.

The fault control panel gives an option for selecting the type of fault to be created. The options available are as follows: 1 – No fault; 2 – Phase A to Ground fault; 3 – Phase A to Phase B fault. These options are chosen manually based on the requirement.

B. Hardware Development

Induction motor faults due to the mechanical origin are directly related to motor vibration. The main source of mechanical fault is the rotor. However, the presence of any type of mechanical faults in the rotor causes a level of rotor vibrations, but it also depends upon stator response and the foundations. Unlike, electrical faults the mechanical fault spectrum cannot be analyzed by changing some of the machine variables such as voltage, current etc. Hence to have a robust analysis for mechanical fault detection a portable hardware is developed for measuring machine vibration.

1) Model Construction

A model is developed to classify the operating condition of an induction motor as either healthy or faulty by measuring the vibration of the test motor. The vibration measured is in terms of acceleration, the acceleration is sensed by the MEMS accelerometer. The available MEMS accelerometers in market today are based on integrated MEMS technology which includes required signal conditioning circuits inbuilt in same IC.

The MEMS accelerometer used is a leadless IC; as devices get smaller and smaller, Surface Mount Devices (SMD) is becoming more popular. Surface mount components attach to the surface of the printed circuit boards, not through holes like older components. SMDs are lighter, cheaper, and smaller.

2) Description of Block Diagram

For actual measurement and storing the vibration data in terms of acceleration the block diagram is as shown in Fig. 4. The induction motor coupled with brake drum is mounted on the motor foundation. The MEMS accelerometer is placed on the induction motor. The MEMS accelerometer is a digital 14 pin IC. The output of the digital accelerometer is given as interrupts. The sensor is interfaced with controller. The vibration data obtained in terms of acceleration in all 3-axis is then stored in the memory card, the data from the memory card is retrieved by inserting the micro SD memory card in card reader. Then the card reader is inserted to the USB of the computer.

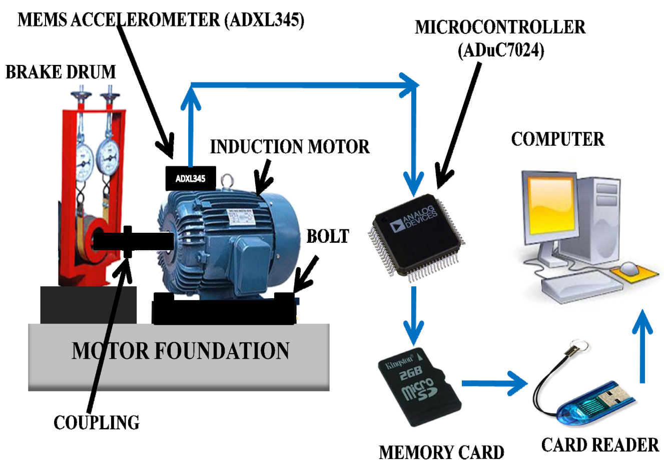

Fig. 4. Structure of Proposed System

3) MEMS Accelerometer for Vibration Sensing

ADXL345 is a small, thin, ultralow power 3-axis accelerometer with high resolution (13-bit) measurement at upto ±16g. it measures the static acceleration of gravity in tilt sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (3.9mg/LSB) enables measurement of inclination changes less than 1.0^0. Several sensing functions provided are 1) Activity and inactivity sensing detect the presence or lack of motion by comparing the acceleration on any axis. 2) Tap sensing detects single and double taps in any direction. 3) Free fall sensing detects if the device is falling. These functions are individually mapped to either of output interrupt pins which are push pull low impedance pins. The default configuration of the interrupt pins is active high. This can be changed to active low by setting the INT_INVERT bit in the DATA_FORMAT register. The major advantage is all functions can be used simultaneously, with only limiting feature that some functions may need to share interrupt pins.

4) Features of the Hardware Developed

- A 2-layer printed circuit board (PCB), 1.20 inches X 2.20 inches form factor.
- A two AAA battery power supply
- A 4-pin UART header to connect to an RS-232 interface cable
- Reset/Download push buttons
- Power indicator/ General Purpose LEDs

5) Experimental Set Up and Procedure

Accelerometer is used for data logging. The term logging describes the measurement, collection and storage of information from sensors. A data logger contains an electrical circuit acting as intermediary between the sensors and the computer. The data-logger provides several functions 1) It can be programmed to collect data automatically 2) It contains its own memory for storing data

Experimental procedure is as follows:

- Insert two AAA batteries into the battery holder
- Insert the micro SD card in the slot.
- Push the on/off switch to the on position to power up the board. The green LED blinks to indicate that the board is logging data.
- When logging is completed, slide the on/off switch to the off position.
- Remove the card from the slot and insert it into the card reader.
- Insert the card reader into the USB port on the computer.
- The acceleration log file is written to the path \XL345\DATA0000.TXT on the micro SD card. The acceleration values are logged in LSB, where the nominal scale factor is 3.9mg/LSB.

III. Results And Discussion

The results are obtained from the methods developed.

A. Simulation Results

1) System Without Fault

Fig. 5. shows the three phase current waveform at the supply side. The y-axis signifies current in ampere and x-axis signifies time in second. From the plot we can observe that the current in all the three phases are uniformly displaced by 120^0 phase shift. This plot clearly shows the current waveform before any fault occurrence in the supply side of the induction motor

Fig. 6 shows the FFT spectrum of the RMS voltage at the supply side of the system before fault occurrence. The y-axis in the plot is the amplitude and x-axis is the frequency. In the plot, the fundamental component alone is dominant. This gives a good indication that there is no voltage harmonic component present in the system except the fundamental component.

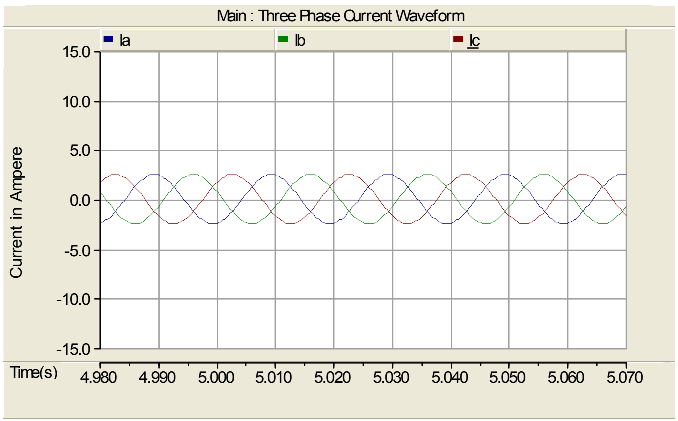

Fig. 5. Three Phase Current Waveform (Without Fault)

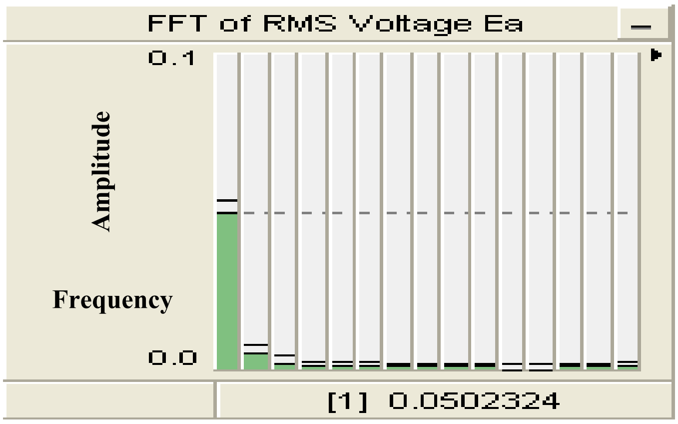

Fig. 6. FFT Spectrum of RMS voltage (Without Fault)

2) System with Ground Fault (Phase A to Ground Fault)

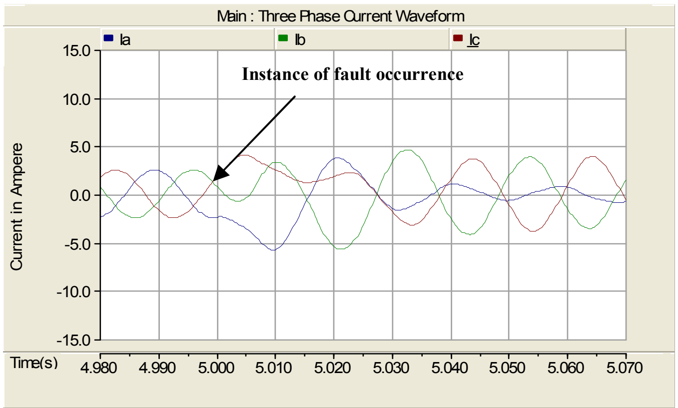

Fig. 7. Three Phase Current Waveform (With Ground fault)

Phase to ground fault is created at 5 second and the fault clearing time is manually given as 20 second. As compared to the three phase current waveform in Fig. 5 the 120^0 phase shift between the three phases are disturbed exactly at the instance of fault occurrence. Comparing the current waveform of both, system without fault in Fig. 5 and system with fault in Fig. 7 current magnitude has increased due to fault occurrence.

FFT spectrum, for the system with phase to ground fault, shown in Fig. 8, there is a fundamental component and a dominant even harmonic present, which clearly shows that whenever there is fault occurrence, there will be a fundamental component and apart from the fundamental component there can be dominant harmonic component.

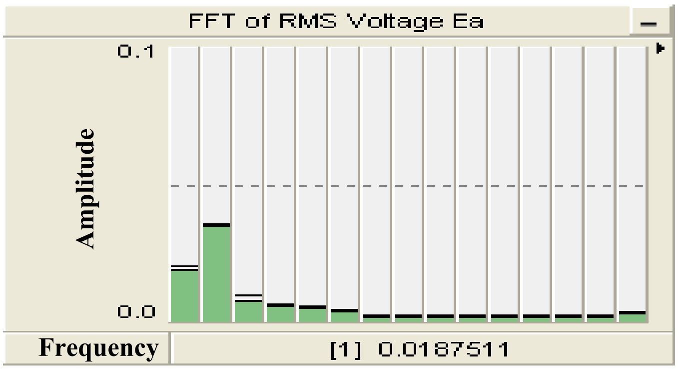

Fig. 8. FFT Spectrum for RMS Voltage (With Ground fault)

3) System with Interphase Fault (Phase A to Phase B Fault)

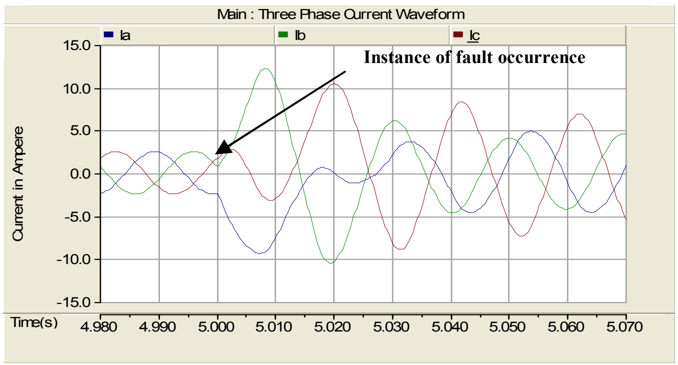

Fig. 9. Three Phase Current Waveform (With Interphase fault)

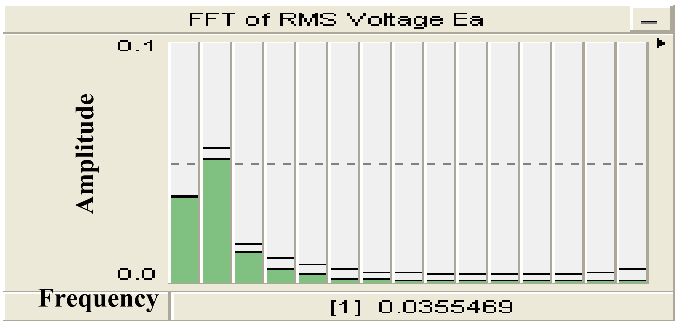

Fig. 10. FFT Spectrum for RMS Voltage (With Interphase fault)

Comparing the current waveform in Fig. 5 with that of the waveform in Fig. 9, the current waveforms are not displaced at 120^0 phase shift, which is a clear indication of an unbalanced system. Similarly, if the current waveform shown in Fig. 7 is compared with current waveform in Fig. 9 the amplitude of fault current is increasing at the instance when phase to phase fault is created. Eventough the three phases are not displaced at 120^0 phase shift, the current drawn during phase to phase fault is high as compared to current drawn when phase to ground fault was created. If comparison is made between the FFT spectrum of phase to ground fault and phase to phase fault shown in Fig. 8 and Fig. 10 respectively, the amplitude of even voltage harmonic compo nent is more in case of phase to phase fault.

There are many different forces and interactions between the stator and rotor. The power source is sinusoidal voltage that varies from positive to negative peak voltage in each cycle. Many different problems either electrical or mechanical in nature can cause vibration at the same or similar frequencies.

A power supply produces an electromagnetic attracting force between the stator and rotor which is at a maximum at a point on the stator when the magnetizing current flowing in the stator is at a maximum either positive or negative at that instance of time. As a result there will be two peak forces during each cycle of the voltage or current wave reducing to zero at the point in time when the current and fundamental flux wave pass through zero. This will result in a frequency of vibration equal to 2F the frequency of the power source (twice line frequency vibration). The simulation results in Fig. 5 to Fig. 10 justify that the presence of machine faults due to electromagnetic origin causes change in mechanical and electrical forces that are acting in the machine. Harmonic voltage distorsion at the motor terminals is translated into harmonic fluxes within the motor resulting in distorsion in the air-gap flux. Some of these harmonics have a dominant value in the vibration spectrum due to the interaction of machine flux harmonics. Although the induced harmonics affects the whole frequency components of the vibration only some components are subjected to change. These frequency components can be used to detect the presence in machine faults which is justified by the presence of twice line frequency component during the occurrence of electrical faults.

B. *Experimental Results*

For detection of mechanical faults experiments were conducted by placing the accelerometer board on the two test motors. The experiments were conducted for six days continuosly. Each day the motor was made to operate for thirty minutes. Time domain and frequency domain plots were plotted for the motor vibration measured in terms of acceleration. The time domain plot do not give much information regarding severity of the fault and root cause analysis.

The experimental results show the mechanical fault such as mechanical looseness and misalignment. Non rotating looseness causes the highest vibrations compared to other types of faults. The highest vibrations are in the direction where stiffness is smallest, stiffness is usually least in horizontal direction. Loose bolts, rust or cracks results in loose foundation, which may further lead to failure or collision. Looseness can affect the induction motor magnetic circuit by causing variation in the air gap. Such a problem can cause vibration at 2X rotational frequency. The next mechanical fault of our interest are misalignment, this type of fault generates reaction forces and torques in the coupling, and finally torque oscillations and dynamic air gap eccentricity in the driving machine. Moreover, these mechanical phenomena appear at even harmonics of the rotational frequencies of the driven parts. Amplitude and frequency modulations strongly increase in the low-frequency range when a shaft misalignment occurs, and more precisely at even harmonics of the drum rotational frequency.

Fig. 11 shows the FFT plot for a healthy motor, it can be observed that there is an impact or sudden shoot up in vibration amplitude as shown in Fig. 12. There is a sudden shoot up in vibration amplitude at lower and higher frequency. This kind of vibration amplitude rise is not a good sign for reliable motor operating condition. Fig. 13 shows the FFT plot for test motor 2, here the motor is vibrating in all x-, y- and z-axis direction. By tightening the bolts of the motor foundation the amplitude has reduced and this is shown in the FFT plot in Fig. 14.

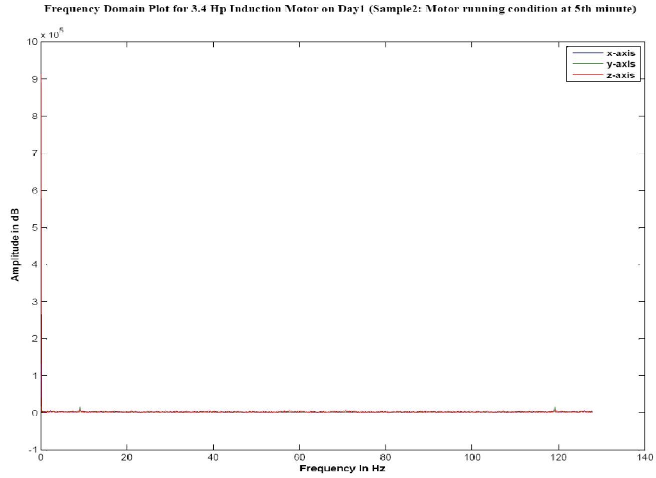

Fig. 11. FFT Spectrum for Test Motor 1 (Healthy Motor)

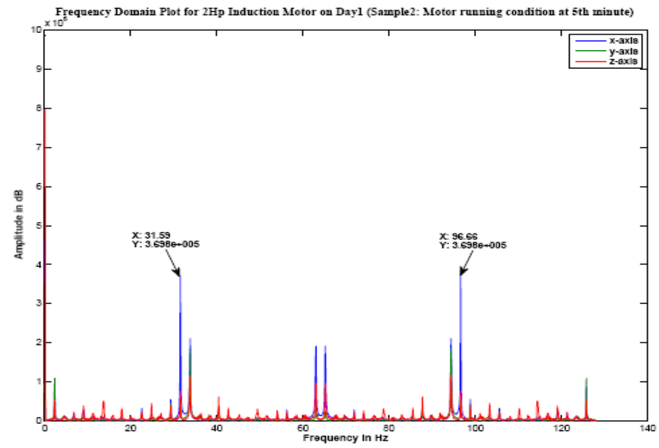

Fig. 12. FFT Spectrum for Test Motor 1 (Healthy Motor)

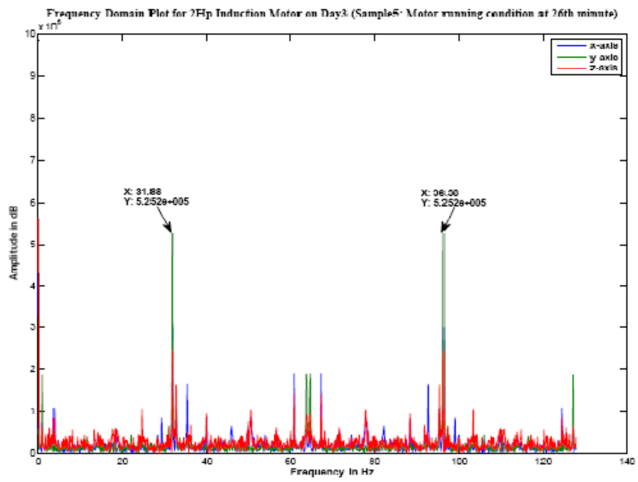

Fig. 13. FFT Spectrum for Test Motor 2 (Before tightening the bolts)

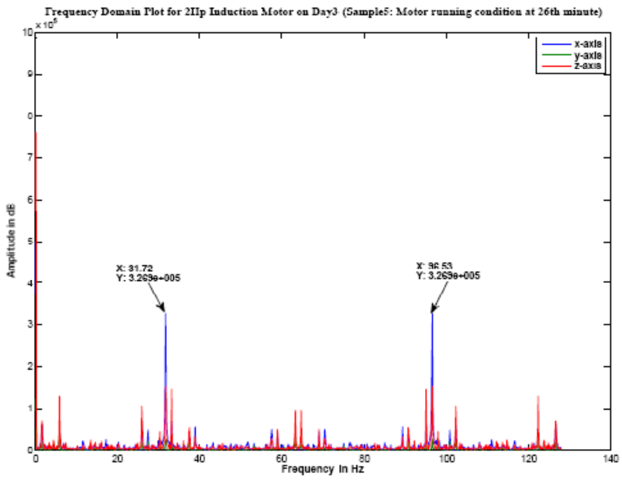

Fig. 14. FFT Spectrum for Test Motor 2 (After tightening the bolts)

The trend plot summarize the characteristics of mechanical looseness, i.e. the looseness have fluctuating amplitude response. Hence, from the trend plots we can say that through out the motor running condition the amplitude is never stable it has always being fluctuating in nature hence the fault detected is mechanical looseness. We can also notice in the same trend plot that the amplitude has reduced after tightening the bolts, referring to Fig. 15 and Fig. 16.

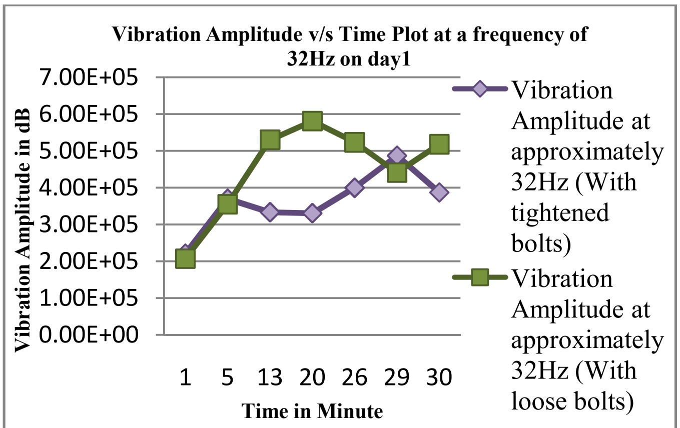

Fig. 15. Comparison of Vibration Amplitude response before and after tightening the bolts on day1

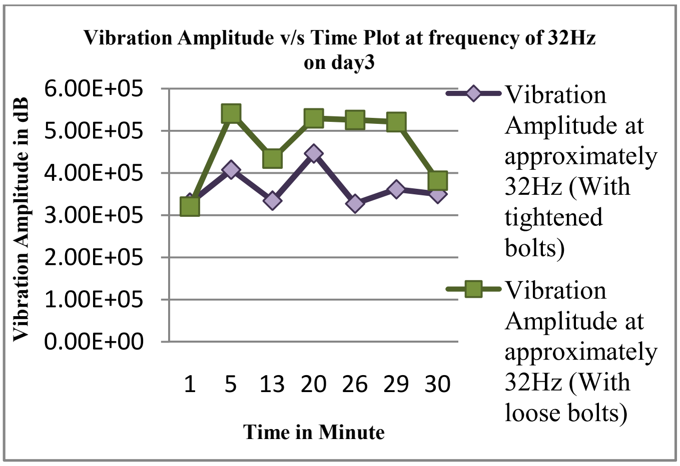

Fig. 16. Comparison of Vibration Amplitude response before and after tightening the bolts on day3

IV. Conclusion

Vibration analysis provides reliable detection of faults in all types of electric machinery. Vibration analysis techniques combine the possibility for fault detection (by revealing excessive machinery vibration), diagnosis of vibration problems in the machinery, and faults in the machinery electromagnetic system, including internal and external electromagnetic anomalies. PSCAD software is found beneficial for creating electrical faults and for plotting the FFT spectrum. Whenever faults due to electromagnetic origin occur there will be an electromagnetic driving force. This force therefore builds up and dies away twice during each cycle of voltage change and produces a driving force having a frequency exactly twice that of the voltage supply. This driving force causes a periodic distortion of the flux which, through the agency of the stator mounting supports, acts as a driving force to excite vibrations in the frame of the machine. Simulation results justify how voltage harmonics created due to electrical faults causes change in machine vibration. When an induction machine is in a faulty state, vibrations are induced. The usage of the MEMS Accelerometer gives a very low cost solution for vibration sensing. Vibration analysis has successfully identified mechanical and electrical faults in induction motor. Experimental results confirm that a misalignment and looseness in mounting creates additional amplitude and frequency modulations. These phenomena can be easily detected and characterized by analyzing the vibration spectrum.

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