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Vibration signature analysis for Ball Bearing of Three Phase Induction Motor

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Abstract : *Induction motors are lifeline of industries. Failure of induction motor is unbearable since it causes decrease in production, loss in valuable time and above all repairing cost is also to be bared. This needs for early detection of fault with diagnosis of its root cause and that also in working condition so that efficiency can be improved. In this research paper a method has been developed for fault detection in induction motor using vibration measurement. Bearing raceway defects were artificially generated for carrying out a comparative vibration study in healthy as well as faulty conditions. An accelerometer has been used as sensor to measure the vibration level, which is then collected and converted into digital signal with a data acquisition card. The signals are then transformed into frequency domain using FFT and the obtained spectrum is analyzed to determine the condition of the motor and maintenance requirement.*
Keywords - *Ball bearing faults, vibration analysis, FFT.*

I. Introduction

Induction motors are the most important equipment in industry and their reliable and safe operation is desirable. Motor failures in industries cannot be tolerated because they lead to production losses, time consumption and unnecessary repairing costs. This motivates the concept of condition monitoring. In general, detection and diagnosis of incipient faults is desirable for product quality assurance and improved operational efficiency of induction motors, running off the power supply mains. It is reported that defects in core components such as rotor, stator and bearings relate to 88% of motor faults [1]. There are three basic themes of maintenance: Corrective maintenance, time based maintenance and condition based maintenance.

Condition based maintenance inspects the machine at variable time interval and determine the fault on the basis of knowledge of presence or absence of faults. This is the best maintenance approach, since only in this approach unexpected downtime is eliminated and machine is utilized for its full life span thus resulting in economical profit [2]. On line condition monitoring is the process of monitoring and inspecting the condition of machine while it is in normal operating mode. Online condition monitoring detect the changes in the sensory signal which indicate the presence and severity of machine faults and help in deciding the maintenance steps to be taken before breakdown occur. Components of online condition monitoring are sensors, data acquisition, fault detection, fault classification and fault diagnosis.

In the present work, to carry out online condition monitoring, vibration sensors have been used to capture the signal under various operating conditions. After amplification, conditioning and sampling of the data, fault detection is carried out which is based on analysis of acquired signals using Fast Fourier Transform.

II. VIBRATION

Vibrations are generally produced in every rotating machine and are created by the oscillation of mechanical parts [3]. These oscillations are transmitted to the external system, coupled with the machine shaft. When any mechanical part of the motor wears or breaks up, it results in change in oscillations and therefore the vibration spectrum will change. Also any abnormality in air gap flux distribution, changes the torque and hence results in change in vibration pattern [4]. Thus each fault in a rotating machine produces vibrations with distinctive characteristics frequency, which can be measured and compared with the reference ones, in order to perform the fault detection and diagnosis.

2.1 Faults in Induction Motors

Faults in induction motor can be divided into four categories namely broken rotor bar faults (10%), eccentricity faults (12%), stator related faults (38%) and bearing faults (40%) [5]. As it is clear that the majority of the failures in induction motor occur due to its bearing, therefore the present work is focused on detection of bearing faults using vibration signal analysis.

Causes of bearing faults are manufacturing defects, installation errors, lack of lubrication and wear and tear. The ball bearing faults can be classified according to the affected elements. The main elements of ball bearings are as shown in figure 1. The inner ring is mounted on the shaft of the machine and is the rotating part. The raceways against which the rolling elements run depend on the type of rolling elements. The outer ring is mounted in the housing of the machine and in most cases it does not rotate. The rolling elements may be balls, cylindrical rollers, spherical rollers, tapered rollers or needle rollers. They rotate against the inner and outer ring raceways and transmit the load acting on the bearing via small surface contacts separated by a thin lubricating film. The cage separates the rolling elements to prevent metal-to-metal contact between them during operation that would cause poor lubrication. Seals are essential for protection of bearing from contamination and keep the lubricant inside the bearing conditions.

Figure 1. Components of the rolling ball bearing

2.2 Bearing Related Vibrations

Consider an example where the outer race of a ball bearing is flawed because of any of the failure mechanisms. Each time, one of the balls rolls over the flaw, a high-level short duration (impulsive) force is incurred that causes the bearing to vibrate. The excitation and response in bearing occur each time one of the balls rolls over the flaw which generates its own frequency that is of interest in the detection of bearing faults and it can be predicted from the bearing geometry and the speeds at which the inner and outer races rotate. The same is applicable for faults in other components of machine.

For an angular contact ball bearing in which the inner race rotates and the outer race is stationary, the four characteristic frequencies [6] are:

2.2.1 Ball Spin Frequency (BSF)

If roller or ball has a defect such as pit, the pulse repetition rate occurs each time, the defect is struck, is known as the Ball Spin Frequency (BSF)

$$BSF = \frac{N}{60} * \frac{D}{d} * \left(1 - \left(\frac{d}{D}\cos\phi\right)^2\right) \quad (1)$$

2.2.2 Ball Pass Frequency Inner race (BPFI)

If the bearing inner race has a defect such as crack, the fundamental vibration frequency resulting from ball passing over the defect is called Ball Pass Inner Race frequency (BPFI) and obtained as

$$BPFI = \left(\frac{N}{60} * \frac{n}{2}\right) * \left(1 + \frac{d}{D}\cos\phi\right) \quad (2)$$

2.2.3 Ball Pass Frequency Outer race (BPFO)

Similarly, if the bearing inner race has a defect such as crack, the fundamental vibration frequency resulting from ball passing over the defect is called Ball Pass Frequency Outer race (BPFO) and obtained as

$$BPFO = \left(\frac{N}{60} * \frac{n}{2}\right) * \left(1 - \frac{d}{D}\cos\varphi\right) \quad (3)$$

2.2.4 Fundamental Train Frequency (FTF)

Finally, for a defect occurring in the bearing cage, the Fundamental Train Frequency (FTF) is given by

$$FTF = \left(\frac{N}{60} * \frac{1}{2}\right) * \left(1 - \frac{d}{D}\cos\varphi\right) \quad (4)$$

Where 'd' is ball diameter, 'D' is pitch diameter, 'n' is number of balls and 'N' is shaft rotation in RPM. The specifications of the bearings used in the present study are shown in Table 1. :

Table 1: Ball bearing specifications (6206)

S.No.	Parameter	Value
1	Number of Ball 'n'	9
2	Outer ring diameter	62mm
3	Inner ring diameter	30mm
4	Pitch diameter 'D'	42.2mm
5	Ball diameter 'd'	10mm
6	Contact Angle	0 rad

For rolling bearing with surface defects, it is possible to calculate the defect frequency as a defect detection parameter by using the formulas. These defect frequencies have often been used for the diagnosis of rolling bearings by a vibration measurement. In the present study the rotational frequency is 23.3 Hz, inner raceway defect frequency is 135.6 Hz, and outer raceway defect frequency is 74.54 Hz.

2.3 The Experimental Set-up

The purpose of monitoring system is to record the vibration signals from the bearing housing of the motor and to analyse these data using signal processing techniques such as time domain, frequency domain and time-frequency domain techniques [7].

The vibration signals are recorded by running the motor with healthy bearing and then with bearing with known fault. The defect is introduced intentionally in the form of a small hole firstly in the inner raceway and then in the outer raceway of the bearing. These defects were produced by the electron discharge method (EDM). The experimental setup of the data acquisition system is shown in figure 2.

Figure 2.The experimental set up

In this work, the vibration signals of a 3.75 kW, 50Hz, 440 V, 1440 rpm, 4-pole induction motor are recorded with the accelerometer having sensitivity 100mV/g. As the output of accelerometer is of low level and contains unwanted frequencies, therefore some form of preprocessing is required before analysis. The signal conditioning circuit performs a variety of general purpose conditioning functions so as to improve the quality, flexibility and reliability of the measurement system, the signal conditioner is employed in this work.

Before recording the first set of data, bearing in healthy condition is allowed to run under no load conditions. In order to ensure the consistency in signal recording, the data is recoded repeated number of times. The same procedure is repeated for recording the vibrations in faulty bearing. The data acquisition card collects and converts the analog signal into digital signal in order to save the acquired signal into the computer memory. The software for collection of data is developed in LabView.

2 .4 Feature Extraction

The aim of this work is to search the bearing related frequencies as discussed in section 2.3, the recorded vibration signals were transformed from time domain to frequency domain. This is a fundamental step because converting the data to frequency domain enables to obtain frequency plots which can be further used to compare frequency spectrum when no damage is present against the resulting spectrum when damage initiation begins. As FFT is a representation of an image as a sum of complex exponentials of varying magnitude, frequencies and phases [8].

FFT algorithm is applied to the measured data in order to convert it to the frequency domain. The Fourier Transform of a periodic function $X(t)$ is given by:

$$X(f) = \int^{\infty} X(t)e^{j\omega t}\,dt$$

Where ω equals 2πf and f is the frequency component of the signal. The resulting function X(f) is a sum of sine and cosine functions of varying frequencies.

2.5 Analysis of healthy bearing

Figure 3 shows the small record of the vibration signal for healthy bearing condition. The frequency spectrum of the same is given in figure 4. It is clearly visible frequency component at 23 Hz is maximum which corresponds to the rotational frequency of the machine.

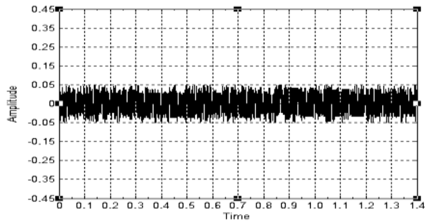

Figure 3: Vibration signal of Healthy Bearing.

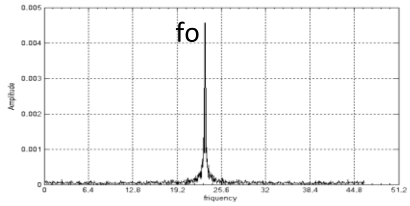

Figure 4: Frequency Spectrum for healthy bearing.

2.6 Analysis of bearing with Inner raceway defect

In the next step of experiment, data for a motor bearing with inner raceway defected was recorded. In case of defective bearing, a increase in vibration levels is observd. The vibration signal of bearing with inner raceway defect is shown in figure5.

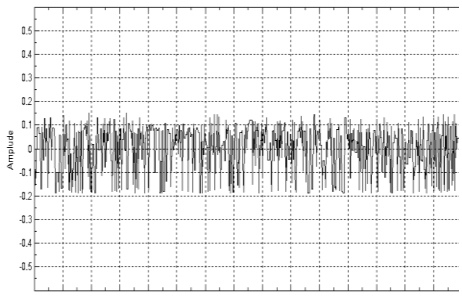

Figure 5: Vibration Signal of bearing with inner raceway defect

Next, FFT was applied to check vibration level in frequency domain against the healthy bearing limits. In case of frequency domain spectrum, figure 6, of bearing with inner raceway defect. it is clearly visible that vibration exceeds the limit and reaches upto 0.09mm/s2 at 135.6 Hz which is inner raceway defect frequency.

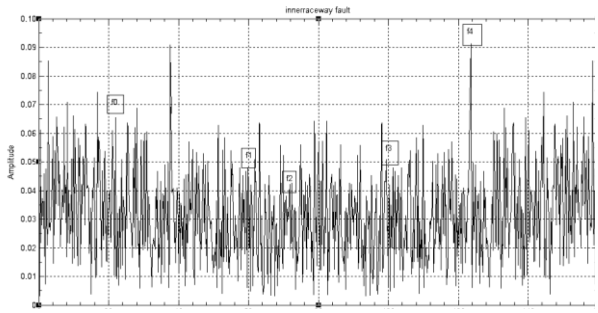

Figure 6: Frequency Spectrum for bearing with inner raceway defect.

2.7 Analysis of bearing with outer raceway defect

In case of bearing having defect in outer raceway the noise and vibrations were far severe than as compared to inner raceway defect. The vibration signal of bearing with outer raceway defect is shown in figure 7.

The frequency spectrum, figure 8, of bearing with outer raceway defect shows peak at 23Hz, 60 Hz, 74.54 Hz ,100 Hz, and 135.6 Hz. The magnitude of spectrum at various harmonic frequencies for bearing with outer raceway defect is quite high and distinct in comparison to healthy bearing. On comparing this spectra with spectra of healthy bearing it is observed that the vibration level at the defect frequency 23.3 Hz becomes 0.02mm/s2 which is 5 times of that observed in healthy bearing.

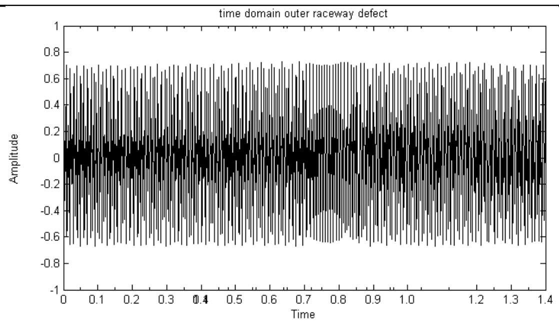

Figure 7: Vibration Signal for bearing with outer raceway defect.

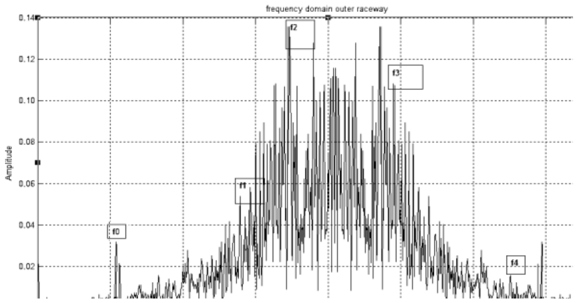

Figure 8: Frequency Spectrum for bearing with outer raceway defect.

It is very important to analyze vibration amplitude, since difference greater than 10% is an indication of bearing problems. Table 2 gives a comparison of vibration amplitudes of healthy and faulty bearings and shows an increase in vibration amplitude and noise in defective bearing.

Table 2: Vibration amplitudes of Healthy and Faulty bearings

Acceleration (mm/sec$^{2)}$	f0	f1	f2	f3	f4
	23.3Hz	60Hz	74.5Hz	100 Hz	135.6 Hz
Healthy Bearing	0.004	-	-	-	-
Bearing with inner raceway defect	0.064	0.048	0.043	0.052	0.092
Bearing with outer raceway defect	0.030	0.060	0.140	0.110	0.017

III. CONCLUSION

Vibration analysis is the most effective technique for monitoring the health of machinery. It offers complementary strength in root cause analysis of machine failure and is natural allies in diagnosing machine condition. It reinforces indications seen in each technique and has unique diagnostic strength in highlighting specific wear conditions.

Trend of overall frequencies and vibration spectrum provide useful information to analyze defects in roller bearings, Trend indicates severity of vibration in defective bearings. Vibration domain spectrum identifies amplitudes corresponding to defect frequencies and enables to predict presence of defects on inner race and outer race of ball bearings. The distinct and different behavior of vibration signals from bearing with inner and outer race defect help in identifying the defects in roller bearings.

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