Preventive Maintenance of Rotating Machines using Signal Processing Techniques

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Abstract*— *This paper presents a method for analyzing the vibration signals of rotating machines and diagnoses preventive maintenance requirements using Vibration Signature Analysis Technique. The concept of Vibration Signature Analysis of Rotating Machines lies on the fact that all rotating machines in good condition have a fairly stable vibration pattern, which can be considered its 'Signature'. Under any anomalous condition of working of such machines, the vibration pattern gets changed. The amount of variation can be detected and the nature of anomalies can be analyzed to get an idea about the malfunctioning of the rotating machine. In order to develop the technique to be applied, it is proposed to simulate the vibration signals of a rotating machines using MATLAB to store the signature of rotating machines under healthy conditions. Deformation can now be introduced in the signature or can be acquired from other sources. Such deformed signals are to be processed in order to know the type of defect the rotating parts of the machine is suffering from. Based on the type of defect, preventive maintenance schedule can be proposed. This paper also aims at overcoming the limitations of traditional Vibration Signature Analysis techniques.

Index Terms*— *Vibration Signals, Signature Analysis, Signal Processing, Rotating machines, Preventive Maintenance.

I. INTRODUCTION

1.1 Background: The rotating machines constitute a major part of the Electrical Machineries in all industries. Various popular rotating machines include: Induction Motors, AC Motor/Generator, DC Motor/Generator, etc. The present study includes Induction Motor as the subject matter of study. The faults in induction motors may be broadly be classified into two groups: (i) Electrical Faults and (ii) Mechanical Faults.

(i) Electrical faults can be sub-divided into following categories:

a) Rotor Fault: Several asymmetries can rise due to the manufacturing by die casting process. Other reasons include non-uniform metallurgical stresses, thermal stresses and stresses due to large centrifugal forces on the rotor.

b) Short turn Fault: Among possible causes, the deterioration of the insulation caused by thermal stress is the main reason for this type of fault.

(ii) Mechanical Faults are mainly due to the manufacturing or fault in design and can be classified as:

a) Air gap Eccentricity: When the rotor is not center-aligned, the unbalanced radial forces can cause the rotor and stator to rub against each other, which could damage both of them. There are three types of eccentricities: Static eccentricity, Dynamic eccentricity and Mixed eccentricity.

b) Bearing Faults: In fact, they are the single largest cause of machine failures. A continued stress on the bearings causes fatigue failures, usually at the inner or outer races of the bearings. This is helped by other external factors such as contamination, corrosion, improper lubrication and improper installation.

c) Load Faults: Motors are often coupled with loads and gears. These faults can arise due coupling misalignment and faulty gear systems.

According to IEEE Standard 493-1997, the most common faults and their occurrences are listed in Table 1.This survey is based on various motors used in industrial applications. Table 1 clearly indicates that most faults occur due to damages in bearings and windings.

Table 1: Statistics of Motor faults

Types of faults	Number of faults/failures				
	Induction Motor	Synchronous Motor	Wound Rotor Motors	DC Motors	All motors
Bearing	152	2	10	2	166
Winding	75	16	6	-	97
Rotors	8	1	4	-	13
Shaft	19	-	-	-	19
Brushes or slip rings	-	6	8	2	16
External device	40	7	1	-	48
Others	10	9	-	2	51

The basic concept of Signature Analysis in the crudest and simplest form is shown in Fig. 2 below.

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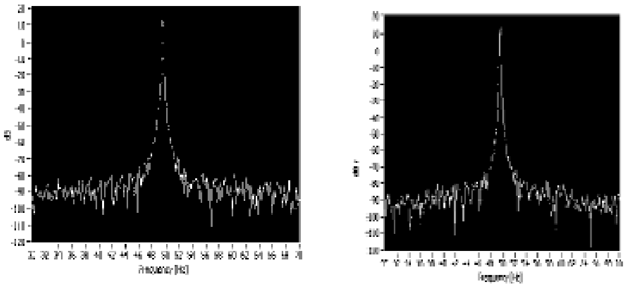

Fig. 3: Signature of a Motor under Test

It shows two samples of Power spectral density plots (dB versus Frequency plots).The first plot corresponds to a healthy motor, while the second one corresponds to a subject under test. By mere empirical observation, it is clear that the signature of the Motor under test does not match completely with the standard signature. Hence, simply by comparing these two Signatures, precisely with the help of a signal processing tools such as those provided by MATLAB, LABVIEW etc., it is both convenient and efficient to differentiate the faulty motors from the healthy ones.

1.2 Literature Review: Recent prominent works in the field of Vibration Signature analysis are attributed to mainly two works: Li et al.[1] carried the vibration analysis with the help of neural networks. The research was done with the help of simulated vibrations and real measurements. In both the cases, results indicated that a neural network can be an effective tool in the diagnosis of various motor bearing faults through the measurement and interpretation of bearing vibration signatures. In this study, the vibration features are obtained from the frequency domain using the FFT technique. Some vibration signatures are constructed from the power spectrum of the vibration signal and consist of the corresponding basic frequencies, with varying amplitudes based on the defect. Researchers pointed out how the neural networks can be effectively used in the diagnosis of various motor bearing faults through the appropriate measurement and interpretation of the vibration signals. Jack and Nandi[2], in their work reported artificial neural network assisted by genetic algorithm technique to sort out the issues of vibration signature analysis very efficiently. In this study, statistical estimates of the vibration signal are considered as input features. By doing this, a very high accuracy of about 99.8% is obtained. However, both the above mentioned techniques are devoted to detecting mechanical faults. Similar approach could also be applied to the detection of the electrical faults using vibration analysis technique.

A brief description of the tools and the idea used by other methods is provided below:

i. Thermal Monitoring: The thermal monitoring of electrical machines is accomplished either by measuring the local or bulk temperatures of the motor. A stator current fault generates excessive heat in the shorted turns, and the heat promulgates the severity of the fault until it reaches a destructive stage. Therefore, some researchers Mellor et al.[3], O.I. Okoro[4] developed the thermal model of an induction motor.

ii. Torque Monitoring: All motors produce air gap torque at some special frequencies .However, it is not possible to measure the air gap torque directly. The difference between the estimated torque from the model gives an indication of the broken bars[5].

iii. Noise Monitoring: Noise monitoring is done by analyzing and measuring the acoustic noise spectrum. Acoustic noise from the air gap eccentricity in induction motors can be used for fault detection. Ellison et al.[5] detected air gap eccentricity fault using this method. However, the noise measurement method is not practical in plants because of the background noise of the operating machinery in the vicinity.

iv. Electrical Monitoring: These methods use the stator currents to detect various types of machine faults. The stator currents can be readily obtainable. Current Signature Analysis, Wavelet Analysis and Current Park's Vector analysis are also used for fault detection[7].

A huge variety of software has been used for the signal processing in the existing signature analysis methods. But, the most widely used are MATLAB and LABVIEW and have been referred to greatly in literature.

The main idea behind this paper is to summarize all the existing information available about Signature Analysis and channelize this available information into the methodology adopted to detect motor faults, described next.

II. METHODOLOGY ADOPTED AND TOOLS USED

Fault diagnosis is the determination of specific fault that has occurred in the system. A typical fault detection method consists of the following stages:

a) Data Acquisition
b) Parameter Extraction
c) Fault Analysis
d) Decision Making

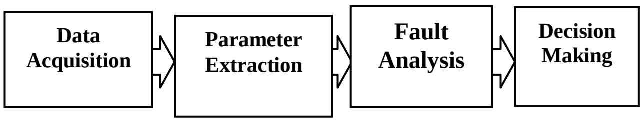

Figure 4: Stages of Fault Detection

The difference among the different method lies in the selection of tools used for these steps as shown in Fig. 4. The steps used are described as follows:

a) Data Acquisition: The vibration pattern of the motor under test is acquired using Data Acquisition Card (DAC). In the present study, vibration signals have been simulated using MATLAB. Deformation can be introduced in the signature or can be acquired from other sources.

b) Parameter Extraction: In order to compare two signals, we must have some parameters for comparison. The parameters used in the present work are: Peak Amplitude, Formant Frequency, No. of Zero Crossing Points and R.P.M. of the Shaft against Time. The more the parameters, the more accurate the analysis will be. This step can also be assisted with the help of Windowing Techniques, if the process of extraction becomes too exhaustive.

Different Windows: The table below gives the equations for different window types.

Window Type **Weight Equation**

Rectangular

$$\omega(n) = 1 ....(1)$$

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$$\omega(n) = 1 - \frac{2\left|n - \frac{M}{2}\right|}{M} \text{.......(2)}$$

Hanning $$\omega(n) = 0.5 - 0.5\cos\left(\frac{2\pi n}{M}\right) \text{......(3)}$$

Hamming $$\omega(n) = 0.54 - 0.46\cos\left(\frac{2\pi n}{M}\right) \text{.....(4)}$$

Blackman

$$\omega(n) = 0.42 - 0.5\cos\left(\frac{2\pi n}{M}\right) + 0.08\cos\left(\frac{4\pi n}{M}\right) \text{.....(5)}$$

Fig.5 shows the Frequency Response and Weight Values of different windows types for a 28th Order (29 weights) low pass filter, with a cut-off frequency of 5000Hz and sampling frequency of 44100Hz.

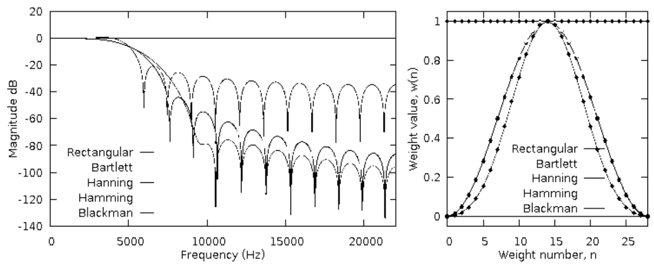

Fig. 5 Frequency response and Weight Values of Different Window Types

a) **Fault Analysis**: There are two distinct approaches to achieve Fault analysis:

Approach 1: Using Look Up Table: As depicted in Fig.6, the parameters extracted for the standard Signature are fed to the Look Up Table

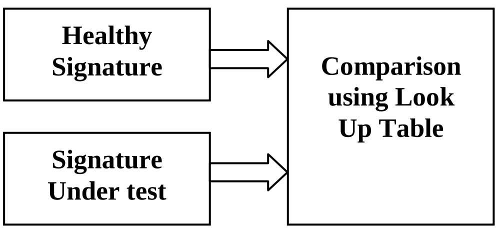

Fig. 6 Look Up Table Approach

Table 2: Look up Table for Standard Signature

Time (Sec)	Peak Amplitude (dB)	No. of Zero crossings	Formant Frequency	RPM of the Shaft
0	**-2**	**1**	**1.33**	**500**
1	**2.2**	**3**	**0.55**	**500**
2	**4**	**9**	**0.45**	**500**
3	**-2**	**14**	**0.3225**	**500**
4	**-2.8**	**20**	**0.208**	**500**

The values of the Parameters are simulated against time and fed to the Look Up Table, as depicted in Table 2. Here, the Look Up Table is a 5*5 matrix that contains the standard values of the Parameters considered. However, five such tables are generated where each table would correspond to a particular Parameter. Similarly, Matrices containing the Parameter values of the Motor under test (Table 3) are also to be generated. By comparing each of the parameter values, High/Low output decision is made accordingly.

Approach 2: Using Neural Networks: Neural networks are used because they are very accurate and efficient. This approach is quite exhaustive and has been depicted in Fig.7.

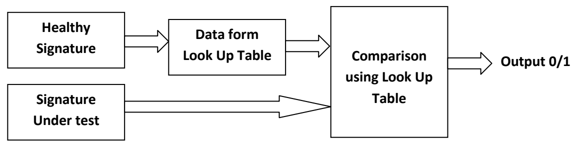

Fig. 7 Neural Network Approach

Table 3: Data for Motor under Test

Time (Sec)	Peak Amplitude (dB)	No. of Zero crossings	Formant Frequency	RPM of the Shaft
0	-5	1	1.33	500
1	2.2	5	0.55	500
2	4	9	0.65	500
3	-2	14	0.3225	550
4	-2.8	20	0.208	450

Here, the Look Up table for the Standard Signature is fed as an input to the neural network. This is done during Training of the neural network. Next, the signatures of the Motor under Test are used for Parameter Extraction. The matrix for the Motor Under test and inputs it to the neural network are generated. Comparing the two inputs, the neural network will produce the output as either 0 or 1. The primary advantage of NN over the Look Up table, apart from efficiency and speed, is that, it can incorporate several advanced features for comparison.

a) **Decision Making:** It can also be done in two ways:
   I: Comparing the Test Signature with Standard Signature
   II: Comparing the Test Signature with Standard Faulty Signatures

In the 1st method, only look up table is to be created which is to be used for comparison. This would allow one to detect whether the motor under test is healthy or not. However, the type of fault cannot be diagnosed.

In the 2nd method, five (or the number of faults to be diagnosed) Look Up Tables are to be created and they are to be used for comparison. This would allow one to identify whether the motor is faulty and also pin -pointedly identify the type of fault.

The tools used for Signal Processing are MATLAB Version: R2009aTool Box/Block set used: Signal Processing

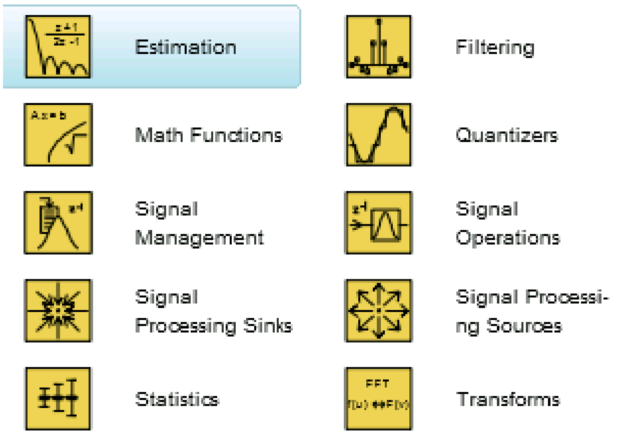

Fig. 8: Signal processing Toolbox

III. SIMULATION USING MATLAB

Steps used:
Step I: To generate a Random signal (s1): This signal is considered as a Standard signature of a Healthy machine.
Step II: To generate another Random signal (s2): This is the deformation applied to be introduced in the Standard Signature.
Step III: To add s1 and s2 to generate (s3): This is the signature of the Motor under Test.
Step IV: To Extract the parameters from s¬1 and to generate a Look Up Table. The Parameter values of the signal s1 are stored in Matrix M1.
Step V: To obtain the parameters of signal (s3): This will also be stored in the Matrix M2.
Step VI: To compare Matrix M1 & M2 for taking a decision.
To generate the Standard Signature: To generate standard signature Either Simulink can be directly used or through Matlab coding the same can be generated.
Using Simulink: Figure 9 depicts the block diagram to generate standard Signature. Signal processing toolbox of Simulink is used to generate standard signature. The following tools are used for generating the Standard Signature:

- Signal generator
- Sine wave
- Random number generator

By properly setting the properties of the above tools so that at the output of the adder, we get the standard desired signature. Fig10 depicts the Standard Signature Generated Using Simulink.

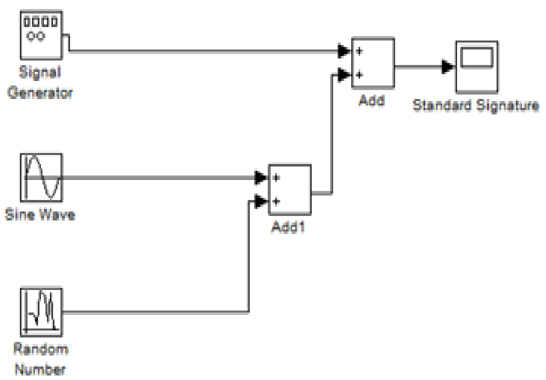

Fig. 9: Block Diagram to generate Standard Signature

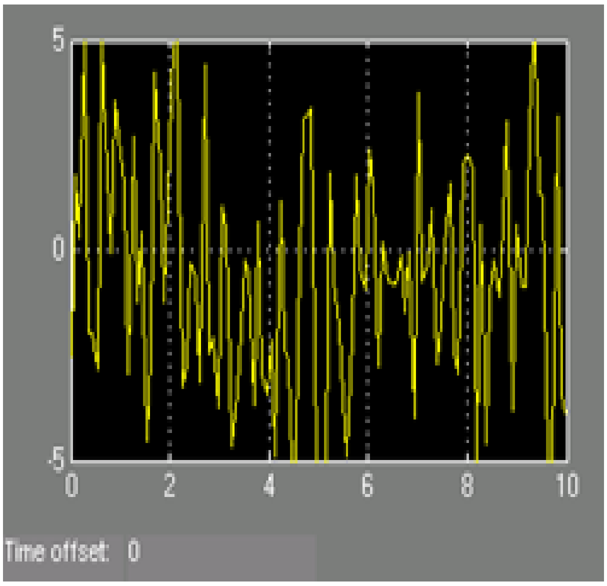

Fig. 10: Standard Signature generated using Simulink

Using MATLAB instructions: Standard signatures can also be generated by writing proper codes in MATLAB. After executing these instructions, the pattern which is considered as standard signature for the present work has been obtained. By selecting proper powers of x inside the cosine function, the standard signature can be varied. A standard signature obtained in this technique has been shown in Fig. 11.

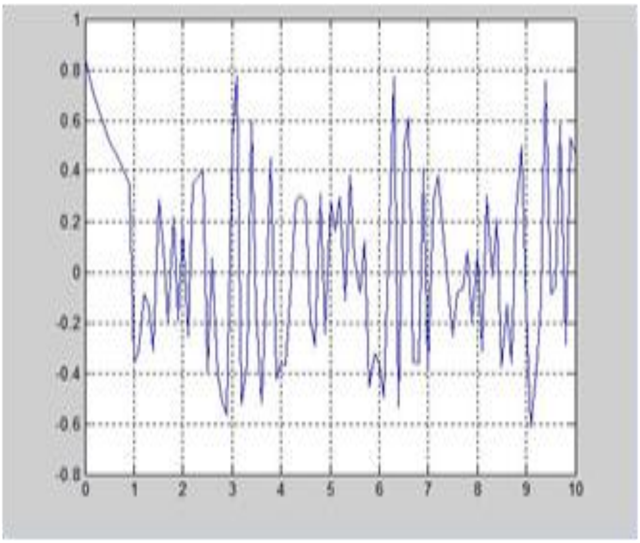

Fig. 11: Standard Signature generated through instructions in MATLAB

To generate Signature under Test:
To generate signature under test signal, a deformation signal is added to the standard signature signal. The deformation signal is due to fault on the rotatary machine (induction motor) in the present case. Fig.12 depicts the block diagram to generate signature of the motor under test and Fig.

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13 shows generated signature of motor under test by Matlab simulation.

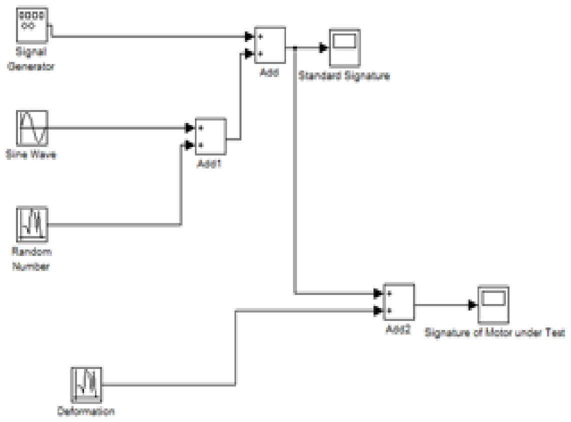

Fig. 12: Block Diagram to generate Signature of the Motor under Test

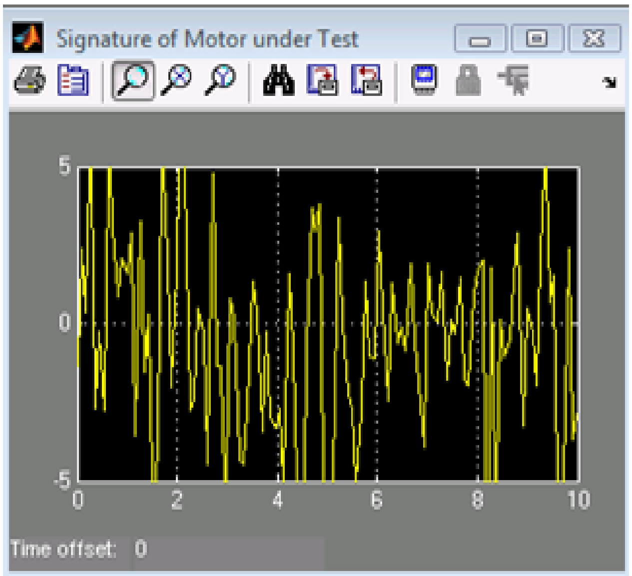

Fig. 13: Simulated signature of Motor under Test

IV. RESULTS AND DISCUSSIONS

A thorough vibration analysis program will provide the following benefits and applications:

a. Dramatic reductions in the high cost of unplanned downtime;

b. Major reductions in spare parts inventory due to better data on machine health;

c. Reductions in emergency work orders and overtime;

d. More efficient repairs because new and reworked equipment can be thoroughly tested;

e. Greater production capacity (more saleable product, fewer rejects);

f. Better plant safety records because machines are not allowed to "run to failure"

Vibration analysis is ideally suited for Motors, Pumps, Fans, Refrigeration machines, Cooling towers, Gear boxes, Emergency generators and Steam turbines. The existing methodology of Vibration Signature Analysis works by tabulating and comparing the values of parameters at all instances of time, manually under human supervision. This obviously is tedious, inefficient and prone to serious errors owing to human limitations. Therefore, if the data acquisition is done under human supervision and the processing and comparison part is handed over to the proposed technique, the overall productivity and efficiency of the maintenance schedule can be greatly improved. Moreover, to make it more efficient, the data acquisition can be done directly using DAS card.

On the flip side, it is also important to note the limitations of vibration signature analysis. As mentioned in literature, first of all, vibration sensors are much costly in the market of developing countries like India. Next, it is a Contact method. These two basic problems associated with the vibration signature analysis denounce its relative importance and usefulness as compared to other methods.

But, it is also important to draw and understand the solutions to above limitations. As for the problem of cost, in total, the cost of vibration sensor is less as compared to the cost of the overall installation and the maintenance schedule. Looking into the overall effectiveness and importance of the entire methodology, it is more feasible to install and maintain the vibration sensors, with the view that the overall productivity is not affected. Next, it is also possible to employ non-contact type sensors, such as Ultra sonic sensors, Optical sensors, Eddy current sensors, etc. to acquire the vibration signals from the machines. This would also lead to multiple use of a limited number of sensors, because these sensors will not be in permanently fixed positions and can be used for other machines as well.

V. CONCLUSION

Vibration signals measured at the external surfaces using suitable transducers contain a great deal of information as to the internal processes. Such signals can be pre-processed using suitable filters and other signal processing techniques to extract certain information regarding the present state of health of the rotating or vibrating parts of the machineries. Changes in the internal condition of rotating machines are often reflected by the changes in the vibration pattern and suitable preventive or corrective measures are applied.

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