Vibration and Current Monitoring for Fault's Diagnosis of Induction Motors

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***Abstract*: In generally, 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. In this paper, the vibration and current of an induction motor are analyzed in order to obtain information for the detection of bearing faults. Significant vibration and current spectrum differences between healthy motor and motors with fault bearing are observed. The high-frequency spectral analysis of vibration and current provides a method to detect bearing faults.**
The effectiveness of the diagnosis system is demonstrated through staged motor faults of electrical and mechanical origin. The developed system is scalable to power ratings and it has been successfully demonstrated with data from 0.75 kW induction motor.

Index terms: diagnosis, induction motor.

INTRODUCTION

The induction machines are widely used for their simplicity, robustness and their low cost. Induction motors are a critical component of many industrial processes and are frequently integrated in commercially available equipment and industrial processes. Because of this, research has been made since long ago to detect a fault that occurs in electrical machines.
Condition monitoring of electric machinery can significantly reduce the cost of maintenance and the risk of unexpected failures by allowing the early detection of potentially catastrophic faults. In condition-based maintenance, one does not schedule maintenance or machine replacement based on previous records or statistical estimates of machine failure. Rather, one relies on the information provided by condition monitoring systems assessing the machine's condition. Thus the key for the success of condition-based maintenance is having an accurate means of condition assessment and fault diagnosis.

Furthermore, these machines can be subjected to different operating conditions that can produce electrical or mechanical damages on the stator and/or the rotor and bearings too. It is well known that the bearing faults constitute a significant part of the faults of the induction motors. This is why research on the faults of these electrical machines has developed many techniques based on the signals analysis applied to measure parameters such as vibrations, noise, power, voltage or stator current. In this paper, we use vibration and noise analysis method to detect the bearing faults.[1] This technique is based on the spectral analysis of current and vibration signals.

The method allows off-line fault detection. In this study, we take into consideration the bearing faults. This type of faults reveals in the vibration spectrum some sidebands, which have specific frequencies. To carry out this analysis, we don't need the most precise model of the machine in order to be able make an effective diagnosis.

It is known the fact that induction motor parameters will change because of the motors' faults**.** That's why these parameters have to be monitored in order to prevent breakdowns.
The major faults of electrical machines can broadly be classified as the following:
· Stator faults resulting in the opening or shorting of one or more of a stator phase windings,
· Abnormal connection of the stator windings,
· Broken rotor bar or cracked rotor end rings.
· Static and/or dynamic air-gap irregularities,
· Bent shaft (akin to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings.

In recent years, intensive research [2] effort has been focused on the technique of monitoring and diagnosis of electrical machines and can be summarized as follows,
· Time and frequency domain analysis.
· Time domain analysis of the electromagnetic torque and flux phasor.
· Temperature measurement, infrared recognition, radio frequency (RF) emission monitoring,
· Motor current signature analysis (MCSA)
· Detection by space vector angular fluctuation (SVAF)
· Noise and vibration monitoring,
· Acoustic noise measurements,
· Harmonic analysis of motor torque and speed,
· Model, artificial intelligence and neural network based techniques.

Vibrations are natural processes in electrical machines and are created by the same dynamic forces.

The human being directly perceives only a small range of low frequency vibrations. The oscillation velocity is turning the vibration into noise. The growth of air pressure is proportional to the velocity of the oscillating surface. That is why the standards generally limit the oscillation velocity of electrical machines. This also limits the noise**.**

Vibration and current analysis is a remote, not-intrusive way to test the electrical machine *being* monitored. It is based on the analysis of the vibration and current waveform using complex mathematics.

Electrical machines have mechanical parts that oscillate. These oscillations are transmitted to external system coupled with the machine shaft. This results in a machine-related frequency spectrum that characterizes healthy machine behavior. When mechanical part of the motor either wears or breaks up, a frequency component of the spectrum will change. In fact, each fault in a rotating machine produces vibrations with distinctive characteristics that can be measured and compared with reference ones in order to perform the fault detection and diagnosis.

It is known that mechanical problems can cause a motor to seem to have significant electrical problems when being evaluated without vibration analysis. As an example a severely misalign shaft can create a variable air gap between stator and rotor. Therefore it is a good method to make a detailed motor vibration analysis.

Vibration and current monitoring system requires storing of a large amount of data. Vibration is often measured with multiple sensors mounted on different parts of the machine. For each machine there are several typical vibration signals being analyzed in addition to some static parameters like load.

1. VIBRATION AND CURRENT ANALYSIS

1.1 Mechanical problems in induction motors

A great number of mechanical problems can be detected by using vibration and current monitoring. The classical mechanical problems in induction motors are the following:

- Bearing wear and failure. As a result of bearing wear, air gap eccentricity can increase**,** and this can generate serious stator core damage and even destroy the winding of the stator**;**
- High mechanical unbalance in the rotor increases centrifugal forces on the rotor;
- Looseness or decreased stiffness in the bearing pedestals can increase the forces on the rotor;
- Critical speed shaft resonance increases forces and vibration on the rotor core.

1.2 Vibration diagnostics

Vibration control and vibration diagnostics are different practical problems. In vibration diagnostics, the oscillation force that is applied to the defective zone defines the fault and the force is linearly related with the oscillation acceleration. For diagnostics, often both the vibration-acceleration and the vibration-velocity are measured in restricted low frequency ranges.

Most vibration measurements usually use sensors of vibration-acceleration that work based on the piezoelectric effect. For this type of sensors the output electric charge is proportional to the force applied to the sensor.

The vibration signal is converted in electric signals. It is necessary to analyze this signal without loosing the diagnostic information. There are very strict requirements for the analyzing instruments. The operations that the vibration analyzing instruments must perform are the following:

- Measurement of overall vibration level in a standard frequency range and using the units required by these standards.
- Spectral analysis of the vibration, by using FFT.
- Analysis of the oscillation power of separate vibration components extracted preliminary from the vibration signal. The analysis of the spectrum of random high frequency vibration signal is usually used

1.2 MCSA diagnostics

One of the most frequently used fault detection methods is the motor current signature analysis (MCSA). This technique depends upon locating by spectrum analysis specific harmonic components in the line current produced of unique rotating flux components caused by faults such as broken rotor bars, air-gap eccentricity and shorted turns in stator windings, etc. Note that only one current transducer is required for this method, and it can be in any one of the three phases. The motor current signature analysis method can detect these problems at an early stage and thus avoid secondary damage and complete failure of the motor. Another advantage of this method is that it can be also applied online.

Experiments were conducted on defective bearings with scratches on the outer races and bearing balls and cage defects. It has been claimed that all defective measurements were correctly classified as defective. However, the detection procedure required extensive training for feature extraction.

2. BEARING FAULTS MONITORING IN INDUCTION MOTORS

2.1 Techniques for monitoring bearing faults

The analysis of the bearing vibration in electrical machines shows that the forces that occur in the rolling element bearings create the high frequency components of vibrations. In normally working rolling element bearings, the main type of high frequency oscillating forces are friction forces. When a defect develops in the bearing, shock pulses can also be found due to the breaks in the lubrication layer between the friction surfaces.

This method of diagnosing rolling element bearings through analysis of high frequency vibration has many advantages. It makes it possible to locate the defective bearing easier because the vibration signal does not contain any components from other units of the machine.

When a defect of wear of rolling surfaces appears, the friction forces are not uniform. They depend on the rotation angle of the rotating surfaces in the bearing causing the friction forces to be modulated by a periodic process. Periodic shock pulses appear if cavities or cracks appear in the bearing. It is possible to detect the presence of the friction forces modulation and of the periodic shock pulses by the spectral analysis of the envelope of the random vibration produced by these processes. When the friction forces are modulated by a periodic process the harmonic component of the frequency will be found in the measured envelope spectrum. The frequency is determined by the period of the modulating process.

The techniques used to detect the presence of bearings failure are[3]:

-vibration spectrum
-noise spectrum
-monitored stator current – rms value
-monitored stator current spectrum

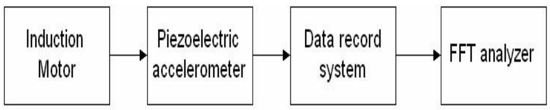

Fig.1. Schematic vibration measurement equipment

Schematic vibration measurement equipment used is present in fig.1

2.2 Monitoring bearing faults in induction motor using vibration and current spectrum

Bearing fault can be detected by analyzing the vibrations in the high frequency spectra[3]. Each type of bearing faults coresponds to a certain vibration frequency.

The ball bearing defects can be categorized as outer race defect, inner race defect, ball defect and train defect and the frequencies to detect these faults are given by[4],[5]:

$$f[Hz] = (N/2) f_r [1 - b_d \cos(\beta) / d_p] \quad (1.1)$$

for an outer bearing race defect

$$f[Hz] = (N/2) f_r [1 + b_d \cos(\beta) / d_p] \quad (1.2)$$

for an inner bearing race defect

$$f[Hz] = d_p f_r / b_d \{1 - [b_d \cos(\beta) / d_p]^2\} \quad (1.3)$$

for a ball defect,

$$f[Hz] = (f_r / 2)[1 - b_d \cos(\beta) / d_p] \quad (1.4)$$

for a train defect.
where:

- f_r is the rotational frequency;
- N is the numer of balls ;
- b_d is the ball diameter ;
- d_p is ball pitch diameter;
- β is the contact angle of the ball.

The analysis of vibration spectrum is used for the detection of bearing faults. The faults detection will be done by comparing two values: the amplitudes of the armonic components obtained from monitoring the vibration spectrum at different frequencies and the amplitudes of the armonic components at the same frequencies obtained from the reference spectrum.

It have shown that these vibration frequencies reflect themselves in the current spectrum as

$$f_{rul} = | f_1 \pm k f_v | \quad (1.5)$$

where k = 1,2,3,… and f_v is one of the characteristic vibration frequencies.

3. THE VIBRATION AND CURRENT SIGNATURE OF INDUCTION MOTOR

The motor tested in this paper is a 0.75kW induction motor.

The induction motor is equipped with 6202 ball bearing type having the number of balls N=8.

The amplitudes of the harmonic components for the induction motor being tested have been calculated according to equations (1.1, 1.2, 1.3, 1.4, and 1.5). Harmonic spectra are generated from collected data by the accelerometer using FFT.

The Fourier fast transform (FFT) is a mathematical operation that is used to extract from a time-domain signal the frequency domain signal representation.

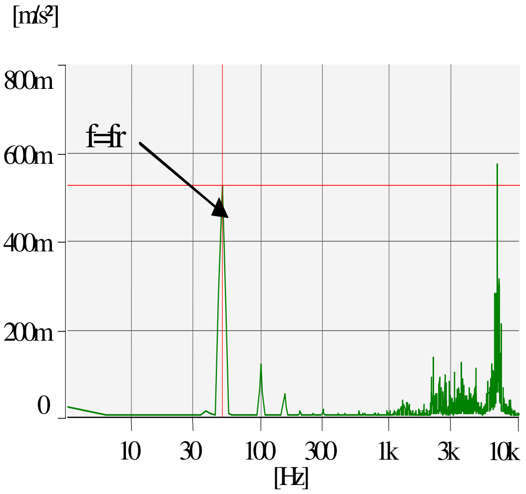

Figure 2 Harmonic vibration spectra for induction motor with "good" bearing

The harmonic spectrum from fig.2 is generated from data obtained by the piezoelectric accelerometer. The electrical machine frame has a mounted piezoelectric accelerometer. This way vibration signals transmitted to the analyzer are very relevant.

The rotational frequency is $f=f_r$=50Hz. The vibration amplitude for this frequency is important and the amplitudes for other frequencies are small.

The analyzed frequencies are f_1=100 Hz, f_2=152Hz and also the bad 200-1000 Hz.

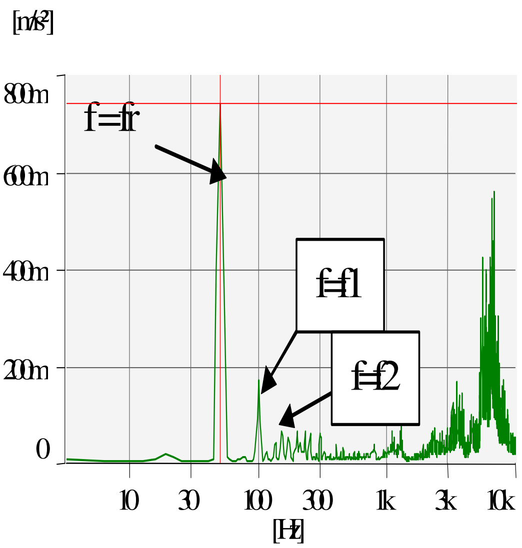

Figure 3 Harmonic vibration spectrum for induction motor with "bad" bearing

The vibration amplitude for the analyzed frequencies, f1, f2 and sideband 150-300Hz, for the induction motor with defective bearing (described in fig.3) is bigger than for the same motor without bearing fault.

It is very important to analyzed vibrations amplitude because difference greater than 10% will be an indication of bearings problems.

Table 1

		f1[Hz] 100	f2[Hz] 152	Average (150-300)Hz
"good" bearing	Vibration amplitude[mm/s2]	0.12	0.042	0.052
"bad" bearing	Vibration amplitude[mm/s2]	0.17	0.054	0.068

In table 1 we make this analysis, and observe an increasing of the vibration amplitude and of the noise in the defective bearing.

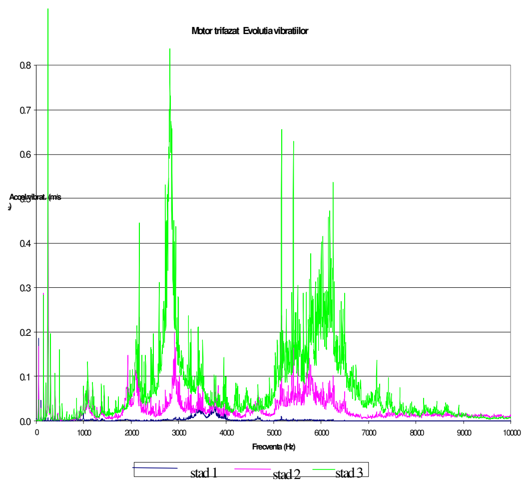

Figure 4 Comparation between harmonic vibration spectrums for healthy and bad bearing

In fig.4 we make this analysis, and observe an increase of the vibration amplitudes in the fault bearing.

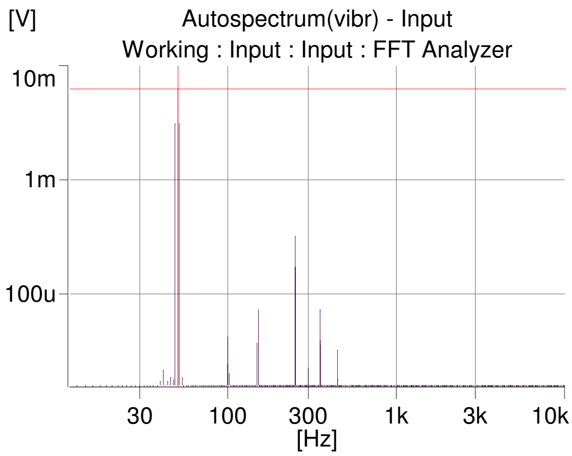

Fig.5 Harmonic current spectrum for induction motor with "health"

The current analysis is very useful for induction motor manufactures in bearing fault diagnosis.

In fig.5 and 6 we present the harmonic noise spectrums for the induction motor with "healthy" bearing and fault bearing.

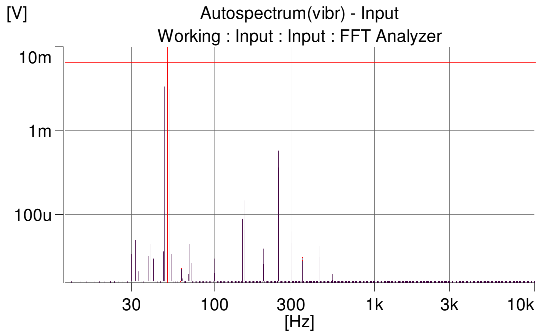

Fig.6 Harmonic current spectrum for induction motor with "bad" bearing

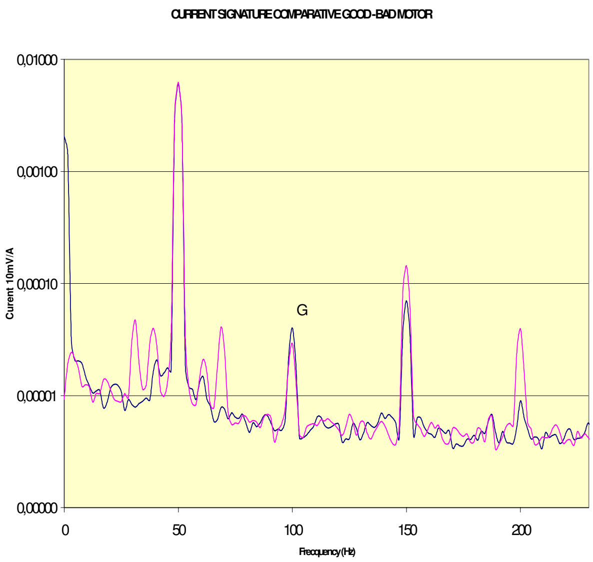

Figure 7 Comparation between harmonic current spectrums for "healthy" and fault motor

By comparing (fig. 7) the harmonic spectrum obtained we observe that the stator current level depends on the state of the bearing**.**

4. NEURAL DETECTOR OF ROLLING BEARING FAULTS

Bearing faults cause specific harmonics in the vibration spectrum of a motor, this frequency depends on bearing geometry and kinematics. Motor current spectrum also contains harmonics specific for different types of bearing faults. These symptoms can be used for different monitoring methods of bearings condition. Specific spectral peaks depend on the type of fault, the rotational speed and bearing geometry.

It is possible to monitor the state of bearings by performing a stator current spectrum analysis. It should be noted, however, that the current spectrum will also contain other components, which result from, e.g. broken rotor bars, air-gap eccentricity, winding distribution, etc. and the frequency components caused by bearing damage are relatively small compared to the other components. So a sufficient spectral resolution is necessary to use the above calculation for bearing diagnosis purposes. These special vibration and/or current harmonics can be used for the training of neural networks and the design of a neural fault detector.

The main task of a neural detector for rolling bearing

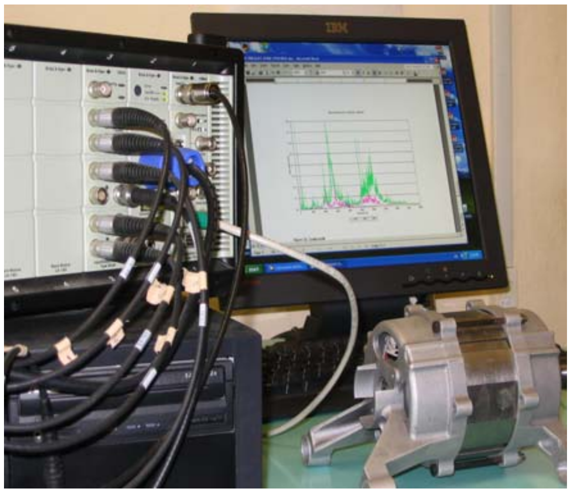

Fig.8 Test bench multianalyser

Fig. 9 Vibration motor's measured

faults was the recognition of the bearing state. The detector should assign the bearing to one of these classes: a healthy or damaged bearing. It was assumed that the input signals of this detector consist of harmonics magnitudes of the vibration spectrum and the stator current spectrum.

The tested bearings were divided into two groups:

- bearings with a priori known failures, assigned

for the training procedure of a neural network a healthy bearing, a train defect, an outer bearing race defect, a bearing with a damaged rolling element;
- bearings assigned for the testing procedure of a neural network: two damaged bearings with unknown failures and one healthy bearing.

The main part of the experimental benchmark was multianalyser (Brüel&Kjær) fig.8. The accelerometer of Brüel&Kjær was mounted on the motor shield and used as a vibration sensor fig 9.

The bearing fault detector was supposed to recognize the bearing state and classify it as one belonging to one of the following groups: healthy or damaged bearings.

Further we present a program that implements a neural network developed with MATLAB. The neural network is designed to diagnose an induction motor, which has bearing faults [6],[7]. For this purpose the software has implemented several functions:

- The program reads the data acquired by the measuring device. At the same time, the program is given the normal data for a healthy motor, which is stored in a file on the disk.
- According with the specialized literature there is a function that calculates the frequencies of interest, with indications about the first motor**.**
- The program calculates the frequencies where the neural network has to "look" for the presence of any sign of faults. Because the values obtained by calculating the frequencies are not always the same with the values obtained from the acquisition stand, we were forced to interpolate the acquired data so that we could obtain a continuous interval of interesting values of frequencies.
- The training data are values of frequencies that are calculated as indicated in specialized literature. From the data for a 'healthy' motor the developed program selects the training information useful for the neural network.
- The actual function that implements the neural network is implemented in a MATLAB program. This program implements a neural network with 10 input neurons. The network has 3 neurons in the output layer. The functions that each neuron implements are for the input layer "sigmoidal tangenta" and for the output layer "linear".

This program is used to analyze an induction motor that, when working properly has as frequency spectrum.

The neural network was used for this purpose:

• the feedforward multilayer network trained with back propagation algorithm,

• the self-organizing Kohonen network with two-dimensional feature map.

In both cases, the inputs of the neural network were characteristic magnitudes of the stator current and/or motor vibration frequencies.

For the feedforward network three types of classifiers were developed:

• the one-output detector for the determination of a bearing condition (healthy –bad) based on the vibration spectrum,

• the one-output detector for the determination of a bearing condition (healthy –bad) based on the current spectrum,

• the one-output detector for the determination of a bearing condition (healthy–bad) based on the noise spectra

In the case of feedforward neural network training it is necessary to present not only input vectors but also target output. For the one-output detectors these outputs are as follows:

• 0: for a healthy bearing,

• 1: for a damaged bearing.

The bearing condition or the supply asymmetry is represented by the output state of neurons in the output layer of feedforward neural detector. In the case of a three-output detector, each output of neural network represents a different condition of the motor: the first output represents a healthy bearing, the second one—a damaged bearing and the third one—supply asymmetry.

Testing the results of the developed neural network detectors based on feedforward networks, trained using vibration spectrum.

CONCLUSIONS

The technique of evaluating the motor condition by performing a FFT of the induction motor vibration has been verified by the experimental results. In this case electric motor vibration motorizing is very useful to detect bearing fault. So, the plant maintenance can easily and successfully detect mechanical fault that lead to unexpected downtime.

A diagnostic procedure using a neural network is described and it is obvious that the development of the neural network and its learning process need a lot of work, but the results are applicable in industry with success.

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