Detection and Diagnosis of Induction Motor Faults by Intelligent Techniques

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ABSTRACT

This paper presents a complete design and implementation of a monitoring system for the operation of the three-phase induction motors. This system is built using a personal computer and two types of sensors (current, vibration) to detect some of the mechanical faults that may occur in the motor. The study and examination of several types of faults including (ball bearing and shaft misalignment faults) have been done through the extraction of fault data by using fast Fourier transform (FFT) technique. Results showed that the motor current signature analysis (MCSA) technique, and measurement of vibration technique have high possibility in the detection and diagnosis of most mechanical faults with high accuracy. Subsequently, diagnosis system is developed to determine the status of the motor without the need for an expert. This system is based on artificial neural network (ANN) and it is characterized by speed and accuracy and the ability to detect more than one fault at the same time.

Key words: induction motor, faults detection, diagnosis, intelligent system.

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الخلاصة

يقدم هذا البحث تصميما كاملا لمنظومة مراقبة حالة المحرك الحثي ثلاثي الطور، تم بناء هذه المنظومة باستخدام الحاسوب الشخصي و نوعين من المتحسسات (التيارو الاهتزاز) لكشف بعض الاعطال الميكانيكية التي قد تحدث للمحرك. تمت دراسة وفحص عدة انواع من الاعطال تتضمن (اعطال المحامل، عدم محاذات محور الدوران) وذلك عن طريق استخلاص بيانات العطل باستخدام تقنية تحويل فورير السريع وقياس الاهتزاز. بينت النتائج ان تقنيتي تحليل بصمة التيار وقياس الاهتزاز لها امكانية كبيرة في كشف معظم الاعطال الميكانيكية وتشخيصها بدقة عالية. بعد ذلك تم تطوير وربط منظومة ذكية للتشخيص قادرة على تحديد

حالة الماكنة بدون الحاجة الى الشخص الخبير. هذه المنظومة تعتمد على الشبكة العصبية الاصطناعية و تتميز بالسرعة والدقة وقدرتها على كشف وتشخيص اكثر من عطل واحد في نفس الوقت.

الكلمات الرئيسية: المحرك الحثي، اكتشاف الاعطال، تشخيص، نظام ذكي.

1. INTRODUCTION

The alternating current machine is an essential tool in our daily lives contemporary, where they are used in many applications. The induction motors are the most popular kind of electric motor used, where up to about (90%) of motor types are used, **Silva, Cardoso, 2005**. It has the largest share in the industrial field because of its advantages, such as ease of installation, cheap price, and the high rate of (power / weight), so it does not need much maintenance. Despite the presence of the high reliability of the induction motors, the operating conditions will be exposed to different faults. The occurrence of any fault will cause operational problems that lead to stoppage of work, and thus lead to losses in production, as well as the risk of the lives of workers. In order to get a good run, and do not reach to these dangerous stages, the monitoring status of machinist (On-Line Condition Monitoring) helps to avoid the problems by monitoring the state and condition of the motor during operation in order to detect and diagnose the fault at early stages of treatment as soon as possible. There are many techniques that are used to detect and diagnose faults; this depends on the type of extract signal. **Dhuness, 2006**. The treatment methods differ depending on the way of digital processing in dealing with these signals, whether dealing with time domain, frequency domain, or time – frequency domain together, or to calculate the root mean square (RMS), and use fast Fourier transfer (FFT). The greatest development in computer programming techniques and smart systems, led to attract the attention of engineers to use it in diagnosis of machine state. The smart systems are characterized by their efficiency and small size as well as high speed in the process of data processing. Many researches deal with motor faults depending upon various mechanisms and techniques. **Yang, 2004**, and **Pole, 2009**.

The main objectives of this paper can be summarized as:

- Designing and implementing of a fault detection system to detect and diagnose the faults of three-phase induction motor based on monitoring current signal technique, and monitoring vibration technique.
- Developing an intelligent system which is able to detect and diagnose the faults, and determine the type and location of the fault, depending on the artificial neural network (ANN), so this system can work accurately instead of an expert person in the diagnosis process.
- Studying the effect of faults on the three-phase induction motors, by working a deliberate real model of faults that is exposed to the motor in order to get a true practical signal for component that results when the fault occurs.
- Study the behavior of the motor during the period of operation, as well as the study of some factors that lead to an increased level of faults.

2. FAULTS OF INDUCTION MOTORS

Induction motors may be exposed to many faults; these faults are classified to external or internal. The external faults occur because of the power supply and the surrounding environmental conditions while the internal faults occur due to damage in one or more parts of induction motor. In addition, these faults can be classified according to their kinds; i.e. mechanical or electrical fault, **Bhowmik, et al., 2013**.

2.1 Ball Bearing Faults

The ball bearing is important parts in all types of motors, the ball bearing consists of four parts (outer race, inner race, balls and cage), and some bearings contain cover for both sides to prevent oil leakage. The ball bearing that is exposed to harsh conditions during the run of motor lead to inadequate performance, these conditions may be mechanical stresses, unbalanced load, lack of alignment of the rotation axis, environmental conditions, rotor unbalance, lack of lubrication, or overload. All these reasons lead to fatigue ball bearing and lead to rise in temperature and increase in vibration and noise, cracking and collapse of the ball bearing. Faults of ball bearing can be divided into two categories, **Zhang, et al., 2008**:-

- Manufacturing defects, they are the result of a bad installation process, such as misaligned races, eccentric races, off-size rolling, and it contains bad parts.
- Local defect, this defect occurs in the case of use the ball bearing for a long time, it includes a number of damages such as cracks, gaps, pits and scratch. It can detect this type of faults by monitoring frequency as a result of vibration, which is calculated from the following relations, **Singhal,** and **Khandekar, 2013**:-

To calculate the frequency due to outer race defect the following equation can be used:

$$F_{ord} = \left(\frac{N}{2}\right) F_{sh}\ (1 - \frac{D_{ball}}{D_{cage}} cos(\beta)) \tag{1}$$

To calculate the frequency due to inner race defect the following equation can be used:

$$F_{ird} = \left(\frac{N}{2}\right) F_{sh}\ (1 + \frac{D_{ball}}{D_{cage}} cos(\beta)) \tag{2}$$

To calculate the frequency due to ball defect the following equation can be used:

$$F_{bd} = \left(\frac{D_{cage}}{2\ D_{ball}}\right) F_{sh} \left(1 - (\frac{D_{ball}}{D_{cage}} cos(\beta))^2\right) \tag{3}$$

To calculate the frequency due to cage defect the following equation can be used:

$$F_{td} = \left(\frac{F_{sh}}{2}\right)\ (1 - \frac{D_{ball}}{D_{cage}} cos(\beta)) \tag{4}$$

To calculate the frequency due to outer & inner race defect the following equation can be used:

$$F_{re} = 2\ F_{bd} \tag{5}$$

The frequencies result directly proportional to the dimensions of the ball bearing and motor speed. **Fig. 1** shows the variables used in the equations for ball bearing defects which under study. Ball bearing passed through several stages until they reach the stage collapse therefore, these stages must be studied to know the age of ball bearing and to find out when the ball bearing need for maintenance or replacement. These stages are:

1. Resonance wave will be generated in the ball bearing frequency.
2. Damage occurs in the outer race or inner race or ball or cage.
3. During this stage, the value of frequency increases in the bearing, and shows harmonics ($2F_{ird}$, $2F_{ord}$).
4. The value of the frequency increases and the show sideband component at this stage must be replaced the ball bearing.
5. The frequencies will appear equal to multiples of the main rotation frequency (F_{sh}, $2F_{sh}$,$3F_{sh}$,…..).
6. The frequencies will appear equal to multiples of the main rotation frequency up to about ($10F_{sh}$). If the noise of the ball bearing has been very high, it must be replaced at the fastest time.
7. During this stage, there are no frequencies because the motor stop working. The ball bearing does not always pass in all stages because sometimes ball bearing is exposed to the harsh conditions of the operator leading to speed up the failure of the ball bearing, such as fluctuation of load, **Mobius Company, 2008.**

2.2 Shaft Faults

The shaft is exposed to a range of faults that cause damage to ball bearing and increase vibration in the motor, **Clarence,** and **Silva, 2005**. These faults are:-

a. Shaft misalignment

This damage is caused by the lack aligns the axis of rotation between the motor shaft and shaft mechanical load, this fault occur because of putting the motor or mechanical load on an unleveled base. It can detect this damage by monitoring the frequency of current and frequency of vibration ($1F_{sh}$, $2F_{sh}$, $3F_{sh}$, …..). This fault can be divided into the following two types:

- Parallel shaft misalignment: This damage occurs because of the parallel motor shaft with mechanical load shaft, and not on one straight line. Displacement, therefore, occurs between the center axis of the motor shaft and the center axis of the mechanical load shaft toward vertical or horizontal direction as shown in **Fig. 2. a**.
- Angular shaft misalignment: It occurs because there is an angle between motor shaft and mechanical load shaft as shown in **Fig. 2. b**.

b. Bent shaft fault

This fault occurs because of unbalanced load, or thermal stresses that lead to curve the shaft and occur of air gap eccentricity fault.

3. METHODS OF FAULTS DETECTION

It is a way to test the motor case by monitoring changes in (temperature, current, vibration, sound, magnetic flux… etc..), during motor operation.

3.1 Current Monitoring

This technique is widely used to diagnose the faults in the induction motors because of the ease of application, high reliability, price licenses, and the need of a few sensors. It obtains a signal of current by choosing suitable sensors for application. The choosing of sensors depends on the sensor type, if the sensor is used to measure, or control, or it is used for the analysis of signal current, and it depends on the type of signal to be measured (AC signal, DC signal). The cost of the sensor varies according to the above factors. There are several types of current sensors, including Shunt Resistance Transducer (SRT), which is the simplest types of sensors, and Current Transformer (CT), which is suitable for measuring the low-lying frequencies. After obtaining the signal current, it detects the fault by using several techniques, some of these technologies are the following, **Gaeid, et al., 2011**.

3.1.1 Motor current signature analysis (MCSA)

It is one of the techniques widely used now, it can easily detect faults, and it needs one sensor. Its working principle is to analyze of an acquired signal current by using one of the signal processing techniques, including analysis of the signal in the domain frequency to monitor the frequency spectrum, or analysis in the domain time or in the domain time-frequency.

3.1.2 Park vector conversion theory

This technique is used to detect faults of unbalance voltage supply and short circuit fault in the stator. The principle of this technique work is to convert the three-phase system into two phase system, then draw two vectors in the plane, where the resulting shape will be circulated if the motor is good and balanced source, but if there is any fault in the source or wires of stator, the output format will be oval, **Ouari 2012.**

3.2 Vibration Monitoring

This technique was a famous technique used a long time ago; it is used to detect faults in electric motors. It now takes an important role in the industrial field because of their ease of use, and it has ability to detect most of the mechanical faults, and some electrical faults. However, this technique has disadvantage because it needs a number of sensors that are in sometimes expensive **Clarence,** and **Silva, 2005**. The working principle of this technique is to measure the vibration signal, or analysis to get the vibration signature. And it is used in this way to measure root mean square (RMS) for the vibration of the signal to compare it with global standards in the table of motor vibration standards according to (ISO 12372), **Mohamadi, et al., 2008**. There are several vibrating sensors that are used for monitoring vibration signal emerging from the motor. These sensors can be divided according to the input signal **Rion Company, 2010**:-

1. Displacement-Vibration Transducer.
2. Velocity-Vibration Transducer.

3. Acceleration-Vibration Transducer.

The acceleration-vibration transducer is a type of sensors that most commonly used at this time, and it was named as the acceleration because of output signal proportional with accelerating. Moreover, the principles of its work are concerned with the conversion of the force supply into an electrical signal proportional to force supply, accordance with Newton's second law (F_M = M×a) **Clarence,** and **Silva, 2005**. Sensor place has great significance in the detection of faults. For example, if the sensor is in vertical position, it will be more sensitive to detect faults of weakness of the motor structure, while in a horizontal position sensor will be more sensible for rotor balance. When putting sensor in axial position, it will be more sensitive to detect the shaft misalignment fault, and bent shaft fault. To overcome these problems, sensors on three axes must be used or use triaxle sensors. **Mobius Company, 2008.** The use of root mean square (RMS), is a simple way, where the value of root mean square (RMS), exceeds the value of the accelerating allowed, this indicates the presence of faults.

3.2.1 Time domain analysis

When the signal analysis is in time domain, the information is taken from the form of the function in the time domain, or by calculating some values by the equations such as, root mean square (RMS). The following equation is used in the calculations in the time domain:-

$$RMS = \sqrt{\frac{1}{N_s} \sum_{n=1}^{N_s} f(n)^2} \tag{6}$$

3.2.2 Frequency domain analysis

When the signal analysis is in frequency domain, the information is taken by noting the frequency spectrum of the signal. There are several techniques for the analysis of signal in frequency space, some of these are, **Al-Hassoon, 2007**:-

1. Fourier series (FS).
2. Fourier transforms (FT).

The focus in the signal analysis in the frequency domain is on the way of fast Fourier transform (FFT).The fast Fourier transform (FFT) is used to reduce the number of calculations compared with the Discrete Fourier Transform (DFT). The number of calculations is equal to (N_s Log_2 N_s). This technique is widely used in all scientific fields, and this type of analysis is used in most analysis devices in industry.

4. INTELLIGENCE SYSTEMS (SMART TECHNOLOGY).

The Artificial Neural Networks (ANN) were well-studied during the past time, it has been successfully applied in the industrial field to monitor and diagnose faults in the motor where it is working rather than an expert in the monitoring process. Also it is faster in data processing and accurate in the diagnosis of fault compared with conventional methods used because it is able to deal with complex relations and it is able to clarify the condition which affects the system that cannot be expressed in mathematical relations. The Artificial Neural Networks (ANN) represents a mathematical tool to deal with the nonlinear changes to bring it closer to the suitable relations by structuring the network and adjusting the weight values within anodes which represents the internal structure of the smart system, **Nelson**, **2004**. There are many types of neural networks, and the system more commonly used is (Feed-Forward Neural Networks) as shown in **Fig. 3**, which can be represented by the following equation, **Patan**, **2008**:

$$Y = F(\sum_{i=1}^{n} w_i \ I_i + b) \tag{7}$$

The detection and diagnosis process consists of four stages:

1- System of data acquisition and signal processing.
2- The process of extracting the information from the signal.
3- The process of detection and diagnosis, fault.
4- The process of classifying the fault type.

Intelligent system is used in the last two steps. Neural network consists of a group of neurons formulated in the form of a layer, and these layers can be divided into three main layers: the input layer through which the data entry, hidden layer which provides the education's ability for the system (it may be more than one layer), and the output layer as shown in **Fig. 4**.The performance of neural network system depends on the relations that contain elements. Each of these elements is trained to perform a specific function, by adjusting the weights and biose of the neurons is achieved.

The first step in training the artificial neural network (ANN), by using (Labview) is developing the network by using various software phrases. Each phrase is customized to deal with one of types neural networks. There are several phrases which are:

- Learning rate (tr).
- Showing the status of training.
- Stopping the training process (Epoch), where the network stops training if the number of iterations equal the number of (Epoch) Limited.
- (Goal) To determine the value of less error.

After the completion process of information, extraction from gaining signal is used by signal processing techniques that are represented by (FFT) technique. It used the artificial neural network system (ANN) to define the relations between the result component and the state of the motor to have identified values of appropriate components (frequency) to detect and identify the faults (amount of the component). The input layer of artificial neural network (ANN) consists of (1920) neurons, and the hidden layer consists of one layer, containing (15) neurons. And the output layer consists of (15) output neurons, with epoch of (1000), and max time (10s), max error (1), and bias (0.9), and the error evaluation is over validation.

5. EXPERIMENTAL WORK

The experimental work contains the faults that are done deliberately in order to simulate the conditions that occur in the motor when the faults are done and shows the techniques used to extract information and analysis of signals in the frequency domain by using fast Fourier transform (FFT), and in the domain time by using the root mean square (RMS). The general layout of the experimental work is shown in **Fig. 5**. The detection and diagnosis system consist of the following items:

5.1 Hardware (Equipment, Tools, and Components).

This includes the following parts:

1. Induction motor, it is an electric three phase induction motor of specifications (1.1KW, 1430r.p.m, 220V, 4Pole).
2. Iron rings, in order to create the detection and diagnosis system, three iron rings wrapped with copper wire were used as current transformers, together with a similar number of iron rings to act as voltage transformers as shown in **Fig. 6**. All the sensors are connected to the data acquisition interface as shown in **Fig. 5**.
3. Vibration sensor of type (Piezoelectric vibration) was attached to the body of the induction motor, as shown in **Fig. 7**.
4. Speedometer used to calculate motor speed as shown in **Fig. 8**. The sensors were linked with the electric motor.
5. Data acquisition interface.
6. Multimeter, in order to measure the current and voltage.
7. DC generator, the generator (2.7A, 110V, 0.297KW, ECC 0.325, 1500 r.p.m) is used to convert mechanical energy into electrical energy as shown in **Fig. 9**.
8. Electrical resistors type of (RHEOSTAT, 50Ω, 10A), is used to increase and decrease the load on the motor by using the power of the electric generator as shown in **Fig.10**.
9. Autotransformer, to change the voltage supply, a 3-phase autotransformer is used.

A general view of the experimental testing system is shown in **Fig. 11**.

5.2 Software

In this work, LabView software is used to implement the program and it includes several steps. The program contains an interface to display faults by lamps arranged in three columns, each lamp is responsible of one kind of faults. They are arranged according to the letters from (A to O). When one of the lamps is active, it means there is a fault. These lamps indicate the following status:-

A- Indicate there is no load, motor health.
B- Indicate there is half load, motor health.
C- Indicate there is a full load, motor health.
D- Indicate there is no load, unbalance of the voltage supply.
E- Indicate there is half load, unbalance of the voltage supply.
F- Indicate there is a full load, unbalance of the voltage supply.
G- Indicate there is no load, fault of shaft misalignment.
H- Indicate there is half load, fault of shaft misalignment.

I- Indicate there is a full load, fault of shaft misalignment.
J- Indicate there is no load, fault of broken rotor bars.
K- Indicate there is half load, fault of broken rotor bars.
L- Indicate there is a full load, fault of broken rotor bars.
M- Indicate there is no load, fault of ball bearings.
N- Indicate there is half load, fault of ball bearings.
O- Indicate there is a full load, fault of ball bearings.

6. SIMULATION OF THE MOTOR FAULTS

6.1 Ball bearing faults

This fault is created by using a set of used ball bearings of the type (6205RS), containing different faults (outer race, inner race, ball, and cage). **Fig. 12** shows the faults of ball bearings. The motor was run in three cases (N.L, H.L, F.L), the bearings have been changed more than once (in order to check the motor at several cases), and the measurements are taken in each case. The frequencies can be calculated using equations (1) through (5), depending on the speed of the motor and the dimensions of the ball bearing. **Table 1** shows the type and dimensions of the ball bearing used, the frequencies are calculated at different speed and load level that are tabulated in **Table 2**.

6.2 Shaft misalignment faults

To create such a sort of faults, a number of thin slides were inserted slide under the motor base at certain angles. And for both cases parallel shaft misalignment, and angular shaft misalignment, many angles is studied and for each case three levels of motor load (N.L, H.L, FL) are considered.

7. RESULTS

7.1 Measuring the Current

7.1.1 Motor with shaft misalignment fault

In the event of shaft misalignment faults for both types (parallel and angular misalignment), the component of vibration (F_{sh}) is transmitting into a current signal, analyzing the current signal is shown in **Fig. 13**. Where a component of rotation frequency and its complications are (F_{sh}, $2F_{sh}$, $3F_{sh}$,….), and the frequency of current signal is (23.5, 47, 70.5,…).

7.1.2 Motor with ball bearing faults

The occurrence of any fault in the bearing caused a generation of a frequency component as illustrated in the equations (1-5). The examination of defective samples of ball bearing is detected and the frequencies are shown in **Fig. 14**. The frequency spectrum in **Fig. 14** shows the presence of the component (78Hz), which represents the component resulting from the defect in the outer race of the bearing (F_{ord}). This indicates that the sample used contains the defect in the outer race. In addition, it is noted that the presence of the component (126Hz) is equal to the value of the component of the fault, plus the value of component wave of source supply.

Some references state that the components of mechanical faults are shown in current signal plus the value of the basic component of source supply, depending on the relation:

$$F_{fault} = F_{defect} \pm f_{supply} \qquad (8)$$

This is clear in **Fig. 14** in which the sample used contains fault in the inner and outer races (F_{re}) at (143Hz), which are equal to the value of the fault component plus the value of the basic component of source supply. The fault component of the cage (F_{td}) was approximately equal to (8.7Hz) and this is not clear in the calculation of frequency, but when adding the value of basic wave frequency (50Hz), it could be found that the value (58.7Hz) was clear.

7.2 Measuring the Vibration

When calculating the value of (RMS) for vibrating signal in the case of health motor, and in the case of faulty motor, so the possibility of knowing the state of the motor, whether it was healthy, or contain the damage, by comparing the (RMS), with (ISO - International Organization for Standardization). **Table 3**, and **Table 4**, shows the value of (RMS), for the motor vibration signal at various loads and different modes of measurement (radial, axial). It is shown that the value of the vibration signal in the case of sensor placed radially-vertical was more sensitive compared with sensor positioned axially, so that sensor in radial form is better than placing it axially at calculating the vibration, except in the case of shaft misalignment. Moreover, motor fault can be detected by note the shape of signal vibration.

7.2.1 Vibration under bearing faults

The vibration signal in the event of a fault in bearings shows that the wave shape will be large deformation. This indicates that the faults of bearing have large effects on the vibrations as shown in **Fig. 15**.

7.2.2 Vibration under shaft misalignment faults

In the event of shaft misalignment faults, both types (parallel shaft misalignment and angular shaft misalignment), reveal a significant change in the shape of the vibration signal compared with the previous faults, as shown in **Fig. 16**.

7.3 Detection and Diagnoses Faults by Intelligent Systems

7.3.1 Normal operation of the health motor

In the case of health motor with full load (F.L), the results were as in **Fig. 17. A**. When trying again with different loads (N.L), (H.L), the result was as in **Fig. 17. B** and **Fig. 17. C**, respectively.

7.3.2 Ball bearing faults

In the case of bearing faults, with full load (F.L), the results were as in **Fig. 18. A** and when it was tried again with different loads (N.L), (H.L), the result was as in **Fig. 18. B**, and **Fig. 18. C** respectively.

7.3.3 Shaft misalignment faults

In the case of shaft misalignment faults, with full load (F.L), the results were as in **Fig. 19. A**. Moreover, when it was tried again with different loads (N.L), (H.L), the result was as in **Fig. 19. B**, **Fig. 19. C**, respectively.

7.3.4 Multi faults (ball bearing and shaft misalignment)

By inserting a number of thin slides under the motor base at certain angles, the motor has a bearing fault. The motor was running for three cases (N.L, H.L, F.L), and the results were taken in each case. With a full load (F.L) the results were as in **Fig. 20. A**. And with different loads (N.L), (H.L), the result was as in **Fig. 20. B**, **Fig. 20. C**, respectively.

8. CONCLUSIONS

According to the current vibration and artificial neural network (ANN) monitoring techniques, it can be concluded that:-

1. The monitoring of motor current technology helps to detect faults by measuring the frequency of the current signal (shaft misalignment, and ball bearing faults) and it seems appropriate to display the components.
2. The motor current signature analysis (MCSA) technique is a technique used in a wide range; also it is good and effective technology in the detection, of the large number of mechanical and electrical faults.
3. The results of vibration monitoring technique also showed the possibility of the diagnosis of the motor case by measuring and monitoring the root mean square (RMS), and comparing it with the standards in the table of (International Organization for Standardization) ISO. In addition, the results showed that choosing the location and direction sensor has an important role in determining the type of fault since some faults appear in a certain direction of the sensor, but they do not appear in the other direction.
4. The use of artificial neural network (ANN) helps in the detection and diagnosis of motor faults at high speed and high accuracy reached to 94% of accuracy.
5. The use of artificial neural network (ANN) is able to detect the compound faults at the same time.

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NOMENCLATURE

b = amount of deviation from the target, dimensionless.

β = contact angle, degree.

D_{ball} = diameter ball, mm.

D_{cage} = diameter cage, mm.

F = frequency power supply, Hz.

F_{bd} = output frequency due to ball defect, Hz.

F_{ird} = output frequency due to inner race defect, Hz.

F.L = full load, dimensionless.

f(n) = signal discrete.

F_{ord} = output frequency due to outer race defect, Hz.

F_{re} = output frequency due to outer & inner race defect, Hz.

F_s = sampling frequency, Hz.

F_{sh} = shaft rotation frequency, Hz.

F_{td} = output frequency due to cage defect, Hz.

F(x) = non-linear transfer function, dimensionless.

H.L = half load, dimensionless.

Ii = the input data, dimensionless.

N = number of balls in the bearing, dimensionless.

N.L = no load, dimensionless.

Ns = number of simple, dimensionless.

Wi = weights coefficients intracellular, dimensionless.

Y = output neural network, dimensionless.

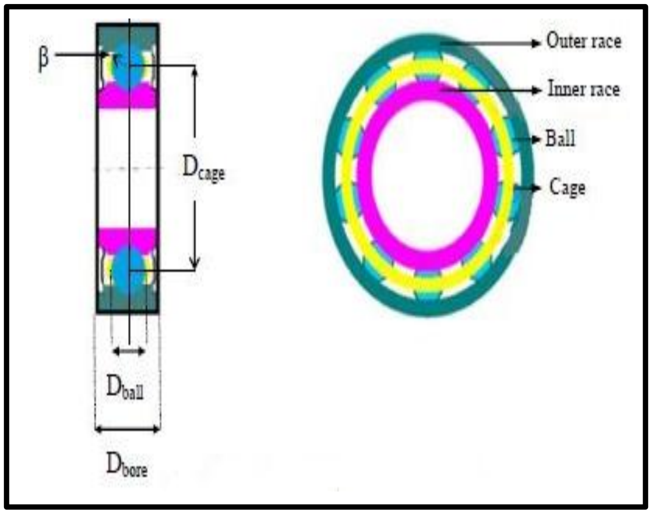
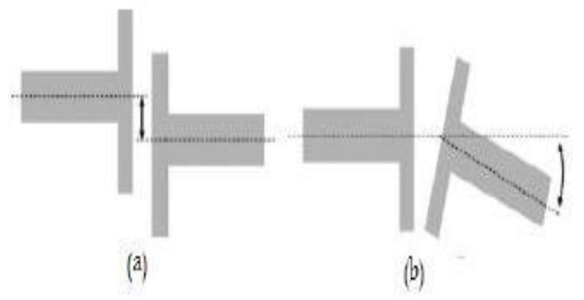


Figure 1. The variables used in the equations for ball bearing



An illustration of (a) Parallel misalignment, (b) Angular misalignment

Figure 2. Type of shaft misalignment

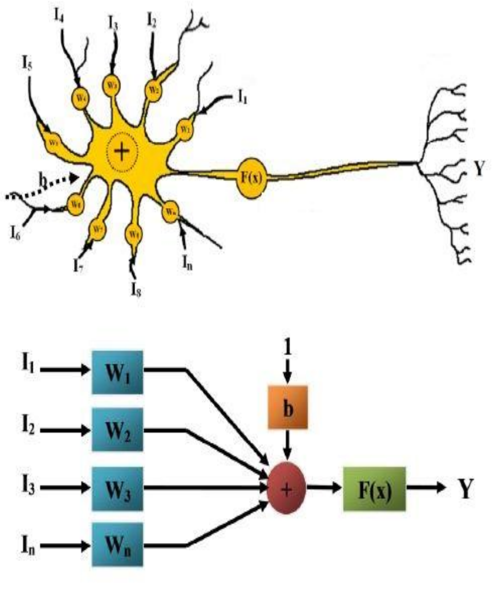


Figure 3. The Mathematical Description for (Feed-Forward Neural Networks).

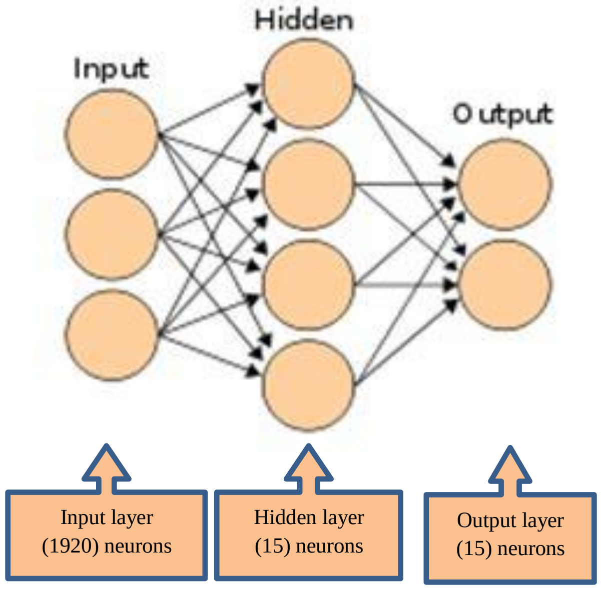


Figure 4. The layers of artificial neural network (ANN), and the way associated together with each

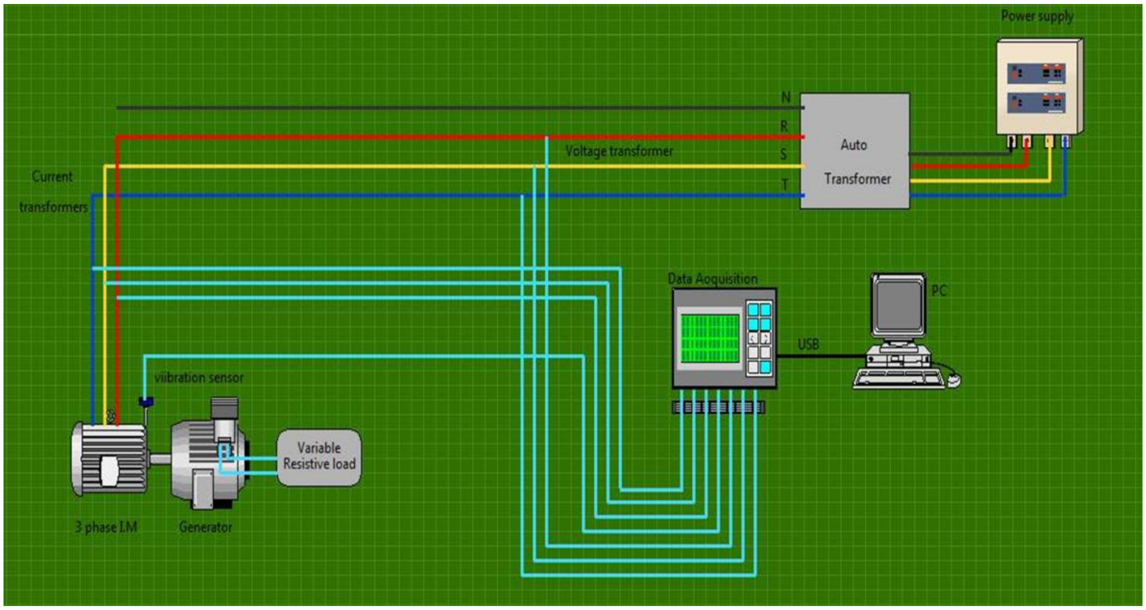


Figure 5. The general layout of the experimental work

(A) Before wrapped

(B) After wrapped

Figure 6. Iron rings

Figure 7. Vibration sensor

Figure 8. Speedometer

Figure 9. Generator

Figure 10. Electric resistance

Figure 11. Detection and diagnosis system

Figure 12. Sample of bearing faults

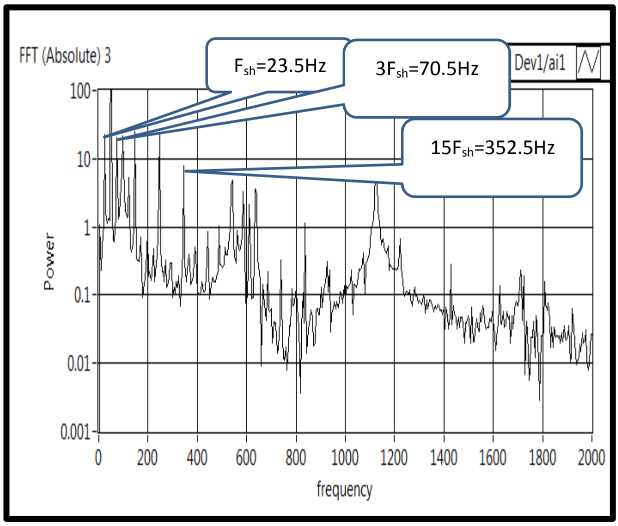


Figure 13. Analysis for shaft misalignment

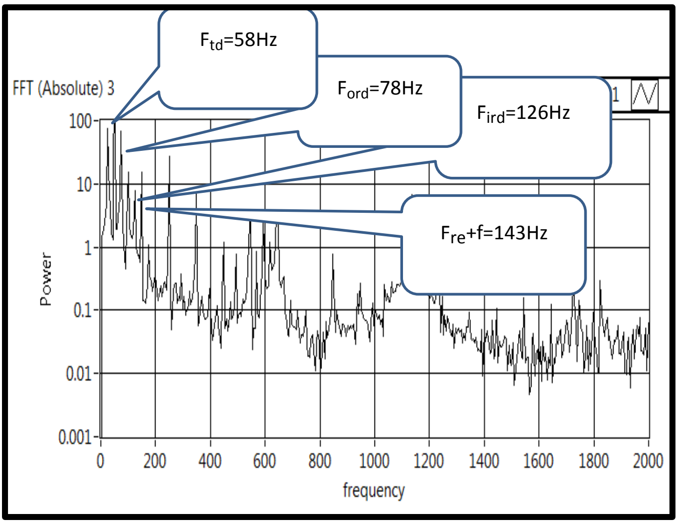


Figure 14. (FFT) Analysis for bearing faults

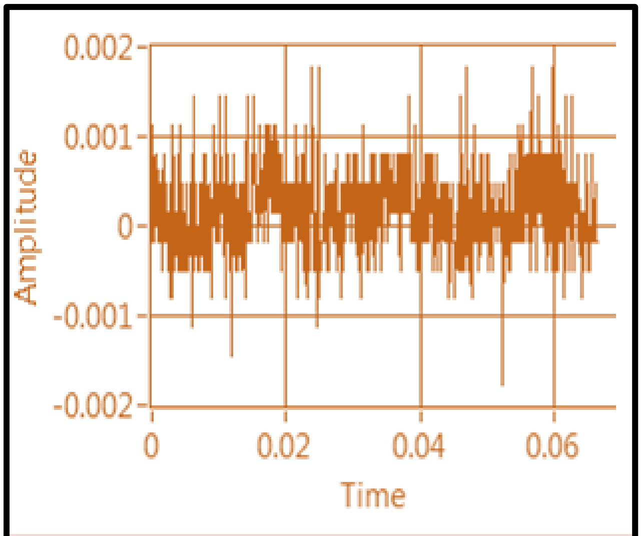


Figure 15. Vibrationsignal in a case of bearing faults

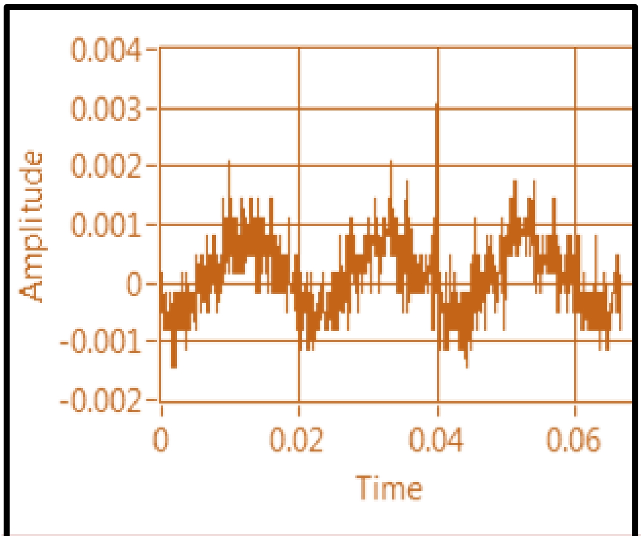


Figure 16. Vibration signal in a case of shaft misalignment faults

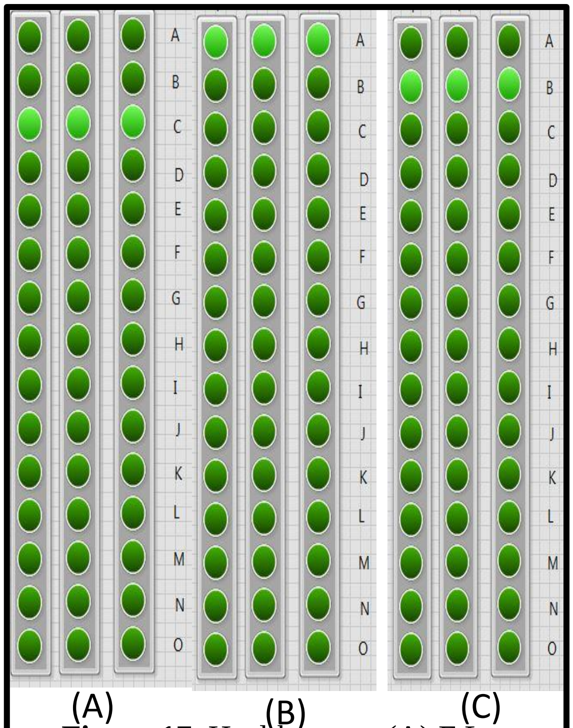


Figure 17. Health motor (A) F.L, (B)N.L, (C) H.L

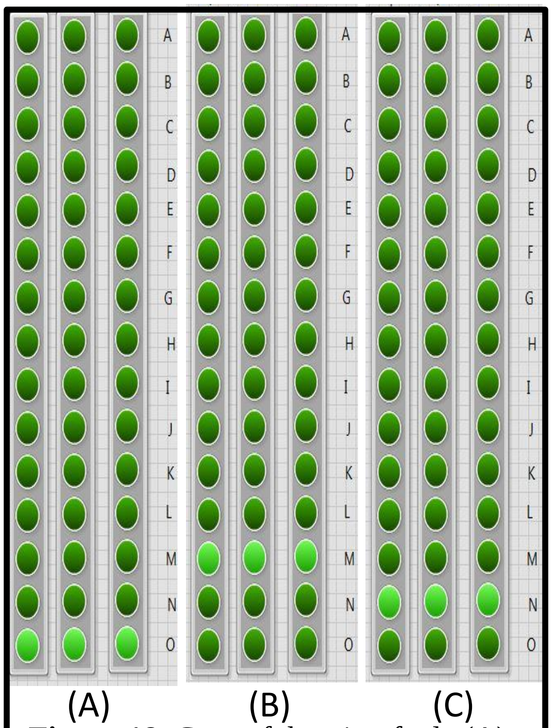


Figure 18. Case of bearing faults(A) F.L, (B) N.L, (C) H.L

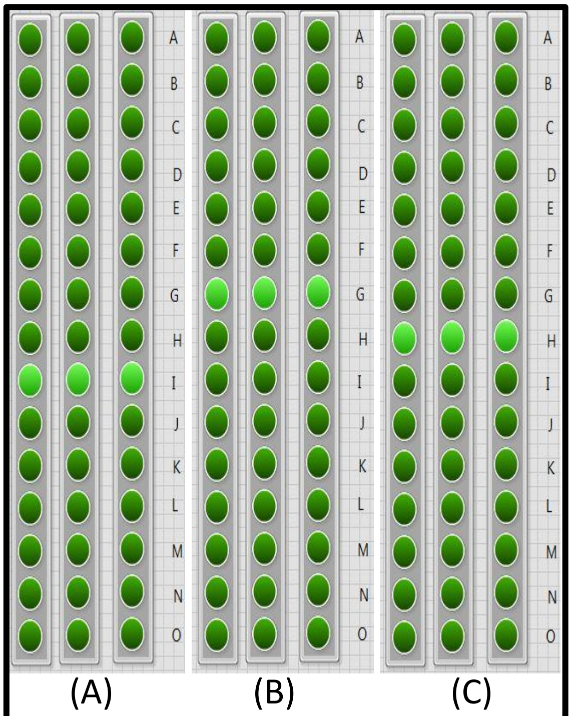


Figure 19. Shaft misalignment faults (A) F.L, (B) N.L, (C) H.L

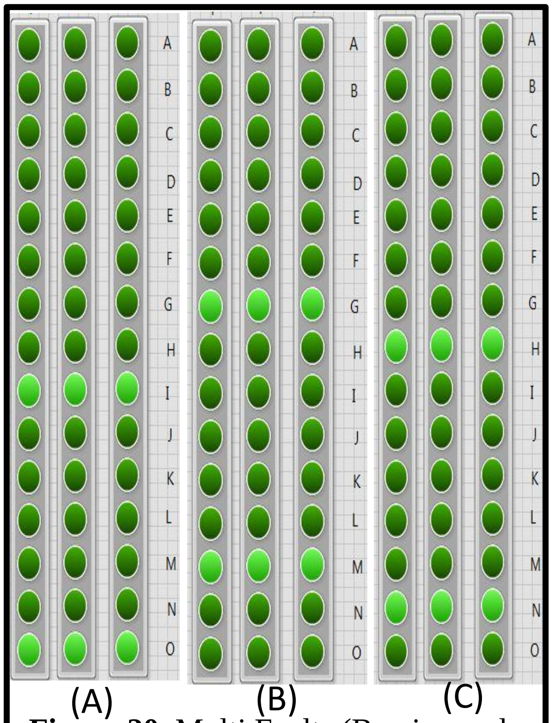


Figure 20. Multi Faults (Bearing and ShaftMisalignment) (A) F.L, (B) N.L,

Table 1. Type, dimensions, defect frequencies for bearing used

Bearing model	6205RS
Number of balls	9
Contact angle (β)	0^o
Outside diameter	52 mm
Inner diameter	25 mm
Cage diameter	38.5 mm
Ball diameter	9 mm
Outer bearing race defect (F_{ord})	3.44Hz
Inner bearing race defect (F_{ird})	5.5Hz
Ball defect (F_{bd})	2.02Hz
Cage defect (F_{td})	0.383Hz
Outer & inner defect (F_{re})	4.04Hz

Table 2. Frequencies for bearing fault

r.p.m	F_{ord}	F_{ird}	F_{bd}	F_{td}	F_{re}
1395	80.12	129	47.2	8.9	94.4
1385	79.3	127.69	46.5	8.8	93
1375	78.96	127.14	46.23	8.75	92.46
1370	78.6	126.58	46.1	8.73	92.2

Table 3. RMS value of vibration velocity (mm/s) when the sensor radial place

Motor case	Value of (RMS)		
	N.L	H.L	F.L
Healthy	0.88	1.3	1.66
Parallel Shaft Misalignment	2.6	2.78	3
Angular Shaft Misalignment	3.3	3.2	3
Bearing	7.5	9.22	10

Table 4 RMS value of vibration velocity (mm/s) when the sensor axial place

Motor case	Value of (RMS)		
	N.L	H.L	F.L
Parallel Shaft Misalignment	1.9	2.85	3.6
Angular Shaft Misalignment	1.31	2.25	2.73
Bearing	5.5	4.8	3.5

Motor case	Value of (RMS)		
	N.L	H.L	F.L
Parallel Shaft Misalignment	1.9	2.85	3.6
Angular Shaft Misalignment	1.31	2.25	2.73
Bearing	5.5	4.8	3.5