DETECTION OF STATIC AIR-GAP ECCENTRICITY IN THREE PHASE INDUCTION MOTOR BY USING ARTIFICIAL NEURAL NETWORK (ANN)

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الخلاصة

تم استخدام تقنية هذا البحث يوضح تاثير اللامركزية الساكنة في الفجوة الهوائية على أداء محرك حثي ثلاثي الاطوار الشبكة العصبية الاصطناعية لكشف هذا العطل ،ان هذه التقنية تعتمد على سعة التوافقيات السالبة والموجبة للترددات. في هذا البحث تم استخدام محركين اثنين وبقدرة (2.2 كيلو واط) لتحقيق العطل بصورة حقيقية وللحصول على البيانات المطلوبة ولثلاث اختبارات (اللاحمل، نصف الحمل والحمل الكامل). تم اعتماد بصمة التيار الساكن لغرض التحليل والكشف عن وجود اللامركزية. تم اعتمادالشبكة العصبية ذات التغذية الامامية وتصحيح الاخطاء بطريقة الارجاع العكسي ، أن سعة التوافقيات السالبة والموجبة للترددات تم اعتمادها لتكون بيانات ادخال لتدريب الشبكة الاصطناعية لغرض الكشف والتمييز بين المحرك العاطل والمحرك الخالي من العطل.

ABSTRACT

This paper presents the effect of the static air-gap eccentricity on the performance of a three phase induction motor .The Artificial Neural Network (ANN) approach has been used to detect this fault .This technique depends upon the amplitude of the positive and negative harmonics of the frequency. Two motors of (2.2 kW) have been used to achieve the actual fault and desirable data at no-load, half-load and full-load conditions. Motor Current Signature analysis (MCSA) based on stator current has been used to detect eccentricity fault. Feed forward neural network and error back propagation training algorithms are used to perform the motor fault detection. The inputs of artificial neural network are the amplitudes of the positive and negative harmonics and the speed, and the output is the type of fault. The training of neural network is achieved by data through the experiments test on healthy and faulty motor and the diagnostic system can discriminate between "healthy" and "faulty" machine.

Index Terms: Static Eccentricity, Three Phase Induction Motor, Artificial Neural Network

INTRODUCTION

Rotating electrical machines play a very important role in the world's industrial life. In petrochemical and power utilities, the failure of electrical motors and generators causes a high cost. This is due to the loss of production, high emergency maintenance costs and lost revenues. Industry's response towards this problem of unexpected interruptions of work is by using "catch it before it fails" approach. The oldest technique for preventive maintenance was tearing the electrical machine down and then looking at it closely. However, taking the motor out of service is costly and time consuming. This is why today's modern industry management is more interested than ever before in adopting new condition monitoring techniques, on-line or off-line, to assess and evaluate the rotating electrical machine's performance condition[1].

The major faults of electrical machines can broadly be classified by the following [1]:

a) Stator faults resulting in the opening or shorting of one coil or more of a stator phase winding.
b) Abnormal connection of the stator windings.
c) Broken rotor bar or cracked rotor end-rings.
d) Static and /or dynamic air-gap irregularities.
e) 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.
f) Bearing and gearbox failures.

The eccentricity fault and it's diagnostic techniques will be discussed briefly in this paper.

The diagnostic methods to identify the above faults may involve several types of fields of science and technology. They were described in references [1, 2] as listed below:

a) Electromagnetic field monitoring, search coils, coils wound a round motor shafts (axial flux related detection).

b) Temperature measurements.
c) Infrared recognition.
d) Radio Frequency (RF) emissions monitoring.
e) Noise and vibration monitoring.
f) Acoustic noise measurements.
g) Motor current signature analysis (MCSA).
h) Model, artificial intelligence and neural network based techniques.

There are different research works in the field of induction machine fault diagnosis include electrical, mechanical, and magnetic techniques. These techniques can be regarded as basis for developing on-line and/or off-line rotating electrical machine condition monitoring systems. Electrical and magnetic techniques include magnetic flux measurement, stator current analysis, rotor current analysis، partial discharges for evaluating stator insulation strength for high voltage motors, shaft-induced voltages, etc. Mechanical techniques include the machine bearing vibration-monitoring systems, speed fluctuation analysis of induction machines and bearing temperature measurement. MCSA for incipient fault detection has received much attention in recent years. For most purposes current monitoring can be implemented inexpensively on any size machine [2].

R.R. Schoen et al. [3] have proposed new method for induction motor fault detection by built on line system utilizes artificial neural networks to learn the spectral characteristics of a good motor operating on line.

M. S. Arefeen et al. [4] presented a similar paper on the analysis of air-gap flux, current and vibration signals as a function of both static and dynamic air-gap eccentricity in 3-phase induction motors. They used the same approach, the air-gap permeance approach, as in [2] for calculating the flux density and unbalanced magnetic forces caused by eccentricity، except that they suggested that the dynamic and static eccentricity should both be considered simultaneously and a new theoretical analysis was presented. Also, it was suggested that in addition to monitoring the line current signature, the vibration analysis should be put forward to identify which particular form of eccentricity is dominant.

X. Huang et al. [5] propose a scheme to monitor voltage and current space vectors simultaneously in order to monitor the level of air-gap eccentricity in an induction motor. An artificial neural network is used to learn the complicated relationship and estimate corresponding signature amplitudes over a wide range of operation conditions.

F. Filippetti et al.[6] presented an induction machine rotor fault diagnosis based on a neural network approach, after the neural network was trained using data achieved through experimental tests on healthy machines and through simulation in case of faulted machines, the diagnostic system was found able to distinguish between "healthy “and "faulty “machines.

H. A. Toliyat et al. [7] have also proposed the detection of air-gap eccentricity in induction machines by measuring the harmonic content in the machine line currents. However, they proposed a new way for modeling the machine under eccentricity. The winding function approach accounting for all the space harmonics in the machine was used to calculate all the mutual and magnetizing inductance’s for the induction machine with eccentric rotors between "healthy" and "faulty" machines.

- Eccentricity Related Faults

Machine eccentricity is the condition of unequal air-gap that exists between the stator and rotor [1,7]. When eccentricity becomes large, the resulting unbalanced radial forces also known as Unbalanced Magnetic Pull (UMP) can cause stator to rotor rub, and this can result in the damage of the stator and rotor. There are two types of air-gap eccentricity: the static air-gap eccentricity and the dynamic air gap eccentricity as shown in Fig. (1). In the case of the static air-gap eccentricity, the position of the minimal radial air-gap length is fixed in space. Static eccentricity may be caused by the ovality of the stator core or by the incorrect positioning of the rotor or stator at the commissioning stage. If the rotor-shaft assembly is sufficiently stiff, the level of static eccentricity does not change. In case of dynamic eccentricity, the center of the rotor is not at the center of the rotation and the position of minimum air-gap rotates with the rotor. This misalignment may be caused due to several factors such as a bent rotor shaft, bearing wear or misalignment, mechanical resonance at critical speed, etc.

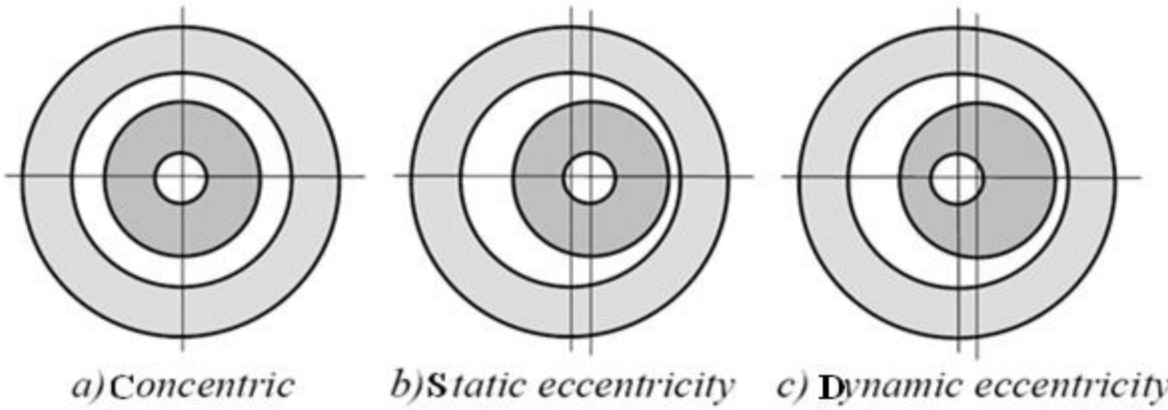


Fig. (1) Eccentricity types

In reality both static and dynamic eccentricities tend to co-exist. An inherent level of static eccentricity exists even in newly manufactured machines due to manufacturing and assembly method, as has been reported by Dorrell [8]. This causes a steady unbalanced magnetic pull (UMP) in one direction. With usage, this may lead to bent rotor shaft, bearing wear and tear etc. This might result in some degree of dynamic eccentricity. Unless detected early, these effects may snowball into stator to rotor hub causing a major breakdown of the machine [9]. The presence of static and dynamic eccentricity can be detected using MCSA. The equation describing the frequency components of interest [1]

$$f_{ecc}= f[(k_1R \pm n_d)(1-s)/p \pm v] \quad (1)$$

where $n_d=0$ in case of static eccentricity, and $n_d=1,2,3,\ldots$ in case of dynamic eccentricity (n_d is known as eccentricity order), f is the fundamental supply frequency, **R** is the number of rotor slots, **s** is the slip**, p** is the number of pole pairs, k_1 is any integer, and **v** is the order of the stator time harmonics that are present in the power supply driving the motor. (v=±1,±3,±5…). In case one of these harmonics is a multiple of three, it may not exist theoretically in the line current of a balanced three phase machine. However it has been shown by Nandi [10] that only a particular combination of machine poles and rotor slot number will give rise to significant only static or only dynamic eccentricity related components. However, if both static and dynamic eccentricities exist together, low frequency components near the fundamental is [11],

$$f_1=|f \pm k_1 f_r|, \text{ where } k1 =1, 2, 3 \ \ldots \quad (2)$$

can also be detected. Mixed eccentricity also gives rise to high frequency components as described by equation (1). Modeling based approaches to detect eccentricity related components in line current have been described in [11]. The simulation results obtained through the models are also well supported by permeance analysis and experimental results. Vibration signals can also be monitored to detect eccentricity-related faults. The high frequency vibration components for static or dynamic eccentricity are given by [7] using an equation similar to (1) (only the values of n_d and **v** are different).

THE EXPERIMENTAL SET-UP

The block diagram of the experimental set-up is shown in Fig. (2), motor specifications are shown in the Appendix, a dc generator of (3kW) rating has been used as a load for the induction motor.

The inputs to the data acquisition are from one of the motor lines as a current and from

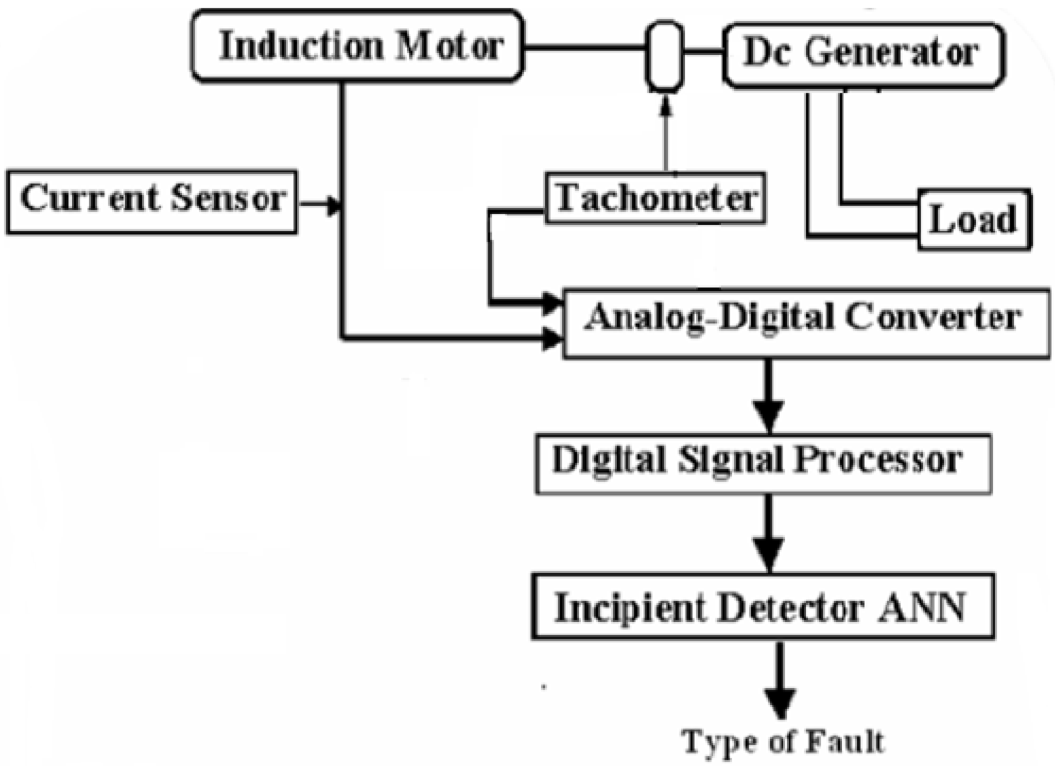


Fig.(2) The Experiment Set for Fault Detection of Induction Motor

the tachometer as a speed; these two inputs signals are converted to voltage signals before using A/D converter. The data of the current and the speed given to the data acquisition circuit the line current measured by using current transformer ratio (10/4) A passing through a resistance of 1Ω which given 4 volt to the data acquisition circuit, then the line current will convert to the frequency domain by using the Fast Fourier in Matlab program package to abtain the sampling frequency and sampling time of the waveform. The speed of the motor measured by using the tachometer will be converted to the voltage value, it's found that the tachometer used in the laboratory give 0.06 volt for each rotation, then by using Equ. 1 to calculate the positive and the negative harmonics frequencies and their amplitudes will be illustrated in the tables, these amplitudes will used to train the neural network to give the incipient detection of the fault.

-EXPERIMENTAL RESULTS

The experiments included three tests (no-load, half load and full load) on both the healthy motor and the motor with eccentricity fault.

Healthy Motor Tests

The line current waveform and the Fast Fourier Transform (FFT) for no-load, half-load and full-load of healthy motor are studied in three different tests these are:

A- No-Load Test

This test involves operating the system at no-load , the values of current , speed and slip were 3.5A, 2950 rpm and 0.0166 respectively. The current waveform and it's FFT are shown in Fig. (3).

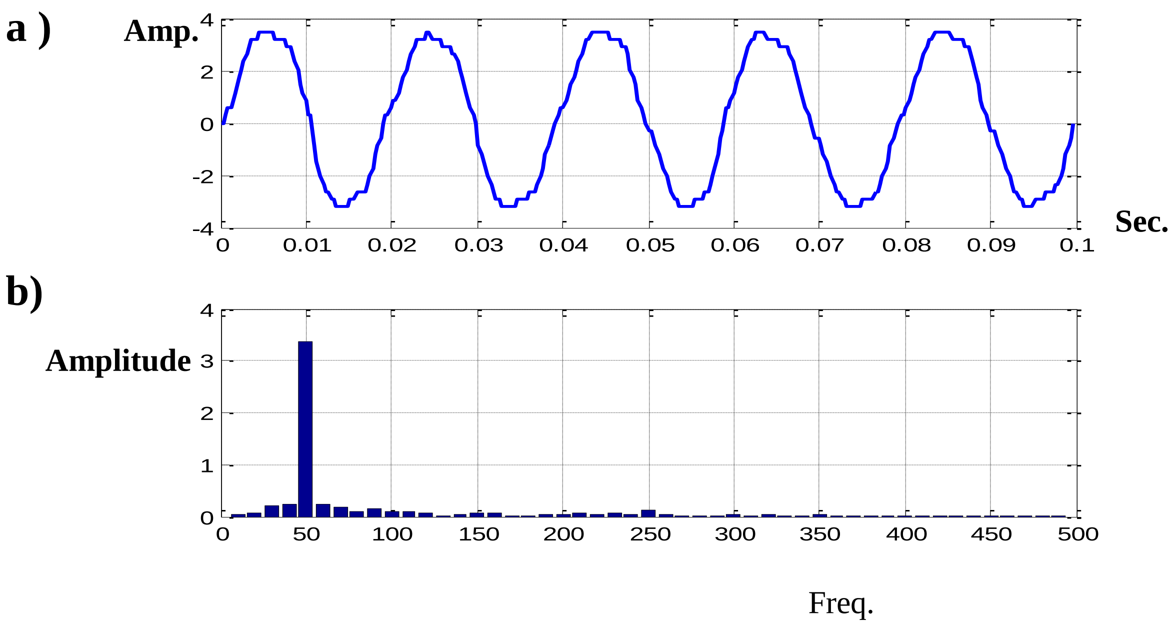


Fig. (3) Current waveform in healthy motor at no-load

a) Line current waveform **b) Corresponding FFT**

B- Half -Load Test

This test involves operating the system at half-load, the values of current, speed, and slip are 5A, 2900 rpm and 0.033 respectively. The current waveform and it's FFT are shown in Fig. (4).

a)

b)

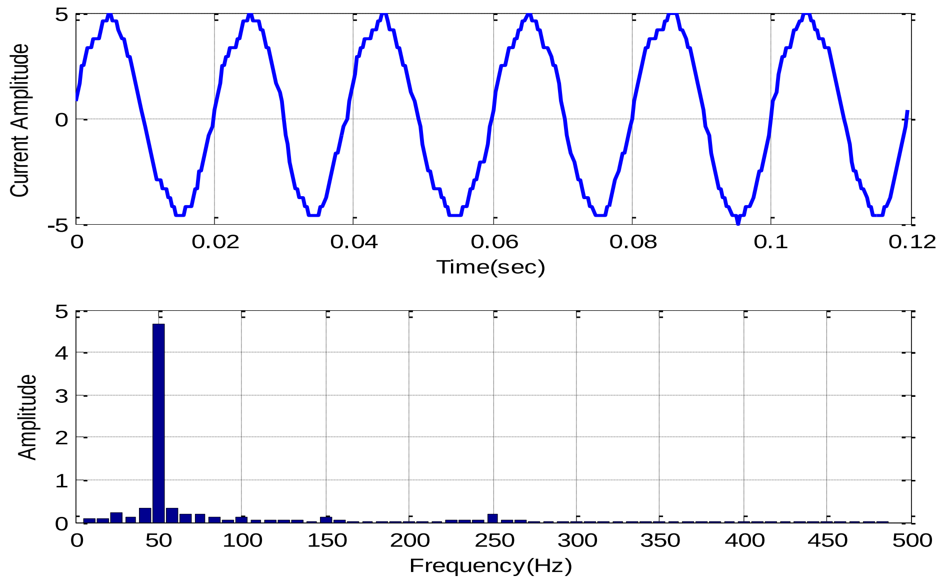


Fig. (4) Current waveform in healthy motor at half-load

a) Line current waveform b) Corresponding FFT

C- Full -Load Test

This test involves operating the system at full-load , the value of current , speed and slip were 8.5A, 2850 and 0.05 respectively . The current waveform and it's FFT are shown in Fig. (5).

a)

b)

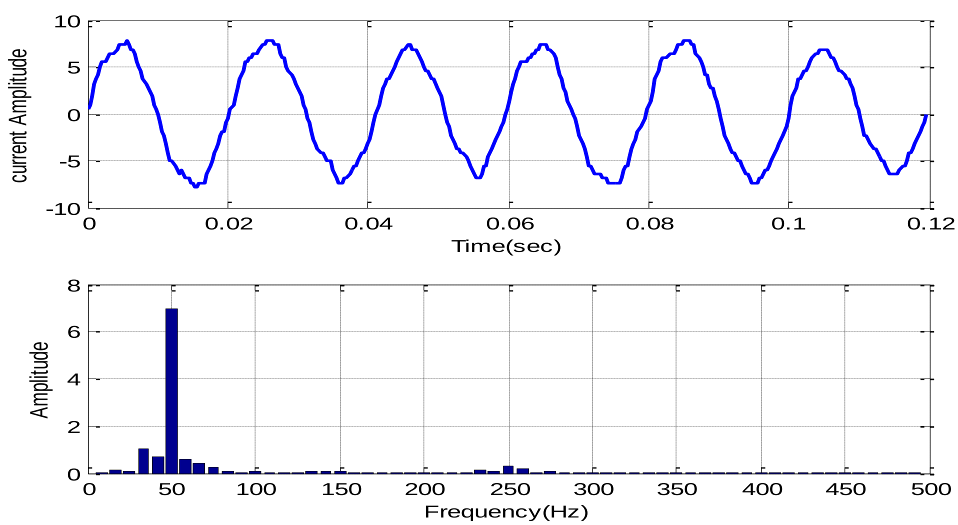


Fig. (5) Current waveform in healthy motor at half-load

a) Line current waveform b) Corresponding FFT

Eccentricity Related Faults Test

The second experiment was eccentricity fault as mentioned before. There are two types of eccentricity dynamic and static. In this experiment the static eccentricity was tested on motor at which the centre of rotor was not at the centre of stator as shown in Fig.(6).The stator line current and it's Harmonic analyses were performed on the acquired data for three cases .Equ.1 is used to calculate side bands frequencies for three cases. All cases for n_d =0 and R=20.

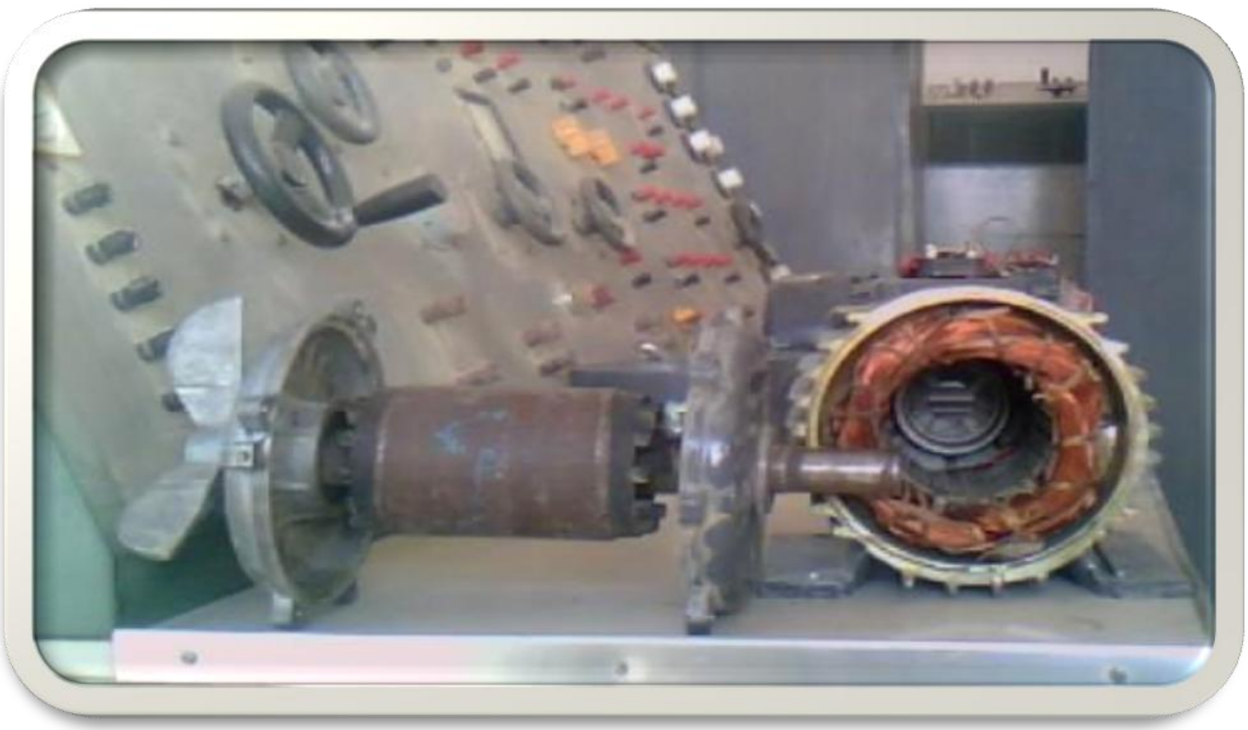
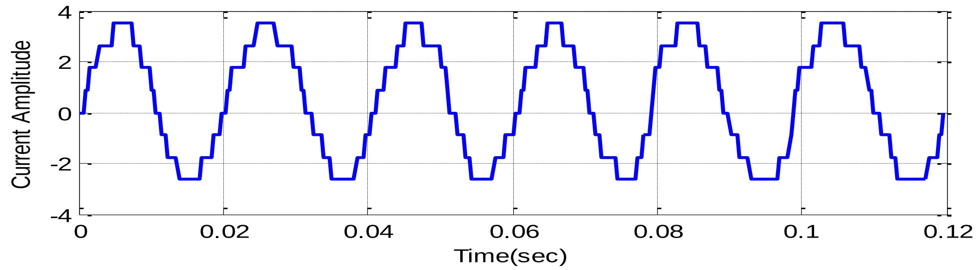


Fig. (6) Side view of rotor eccentricity motor

A- No-Load Test

This test involves operating the system at no-load ,the values of current , speed and the slip are 3.5A , 2810 rpm and 0.063 respectively. The current waveform and it's FFT are shown in Fig. (7).

a)



b)

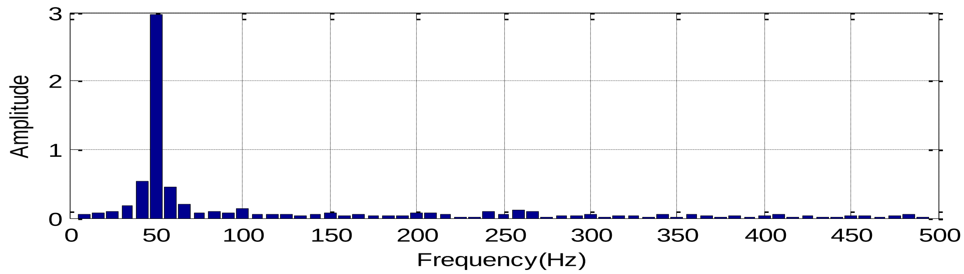


Fig. (7) Current waveform of eccentricity fault at no-load

a) Line current **b) FFT**

Table 1 Illustrates the positive, negative harmonics and their amplitudes for different values of harmonics (v) at no-load, the data of the motor is:

Input Frequency Motor Speed Slip (s) 50Hz
2810 rpm 0.063

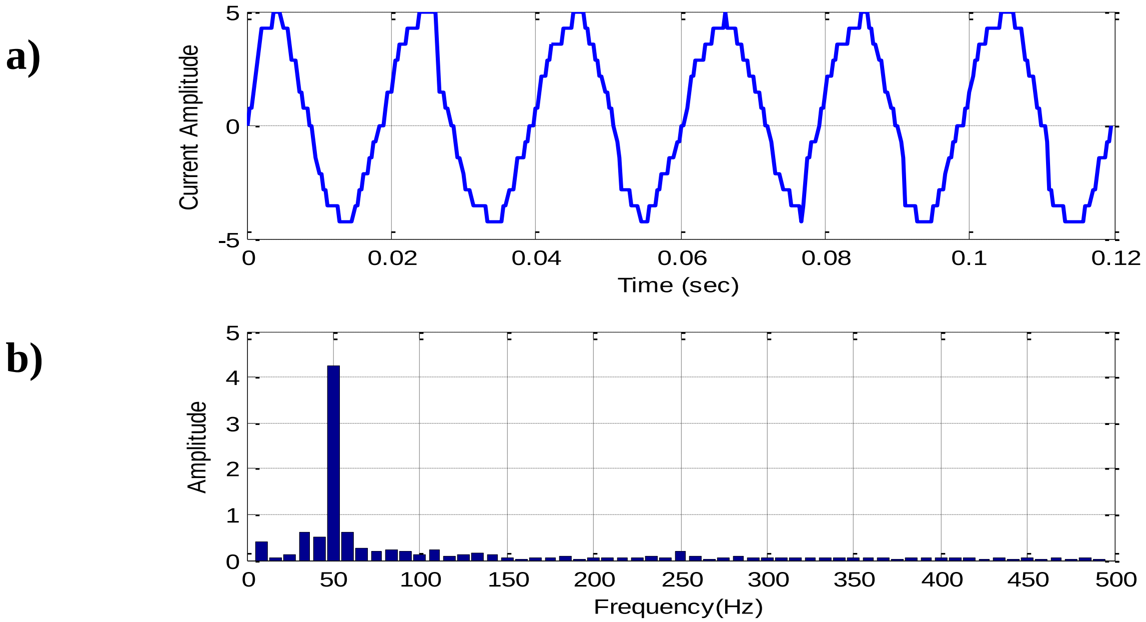
Equation (1) is used to calculate the positive and the negative harmonics and their amplitudes which are given in Table (1).

Table 1 Positive, negative harmonics at no-load (Eccentricity Fault)

v	Pos. Harmonic(Hz)	Amplitude(A)	Neg. Harmonic(Hz)	Amplitude(A)
1	987	0.03	887	0.0168
3	1087	0.0063	787	0.0129
5	1187	0.022	687	0.05
7	1287	0.02	587	0.029
9	1387	0.0177	487	0.019
11	1487	0.0387	387	0.0124
13	1587	0.024	287	0.018
15	1687	0.0234	187	0.04
17	1787	0.0167	87	0.115
19	1887	0.0166	0	0

B-Half-Load Test

This test involves operating the system at half-load, the values of current, speed and the slip are 5A, 2790 rpm and 0.07 respectively. The current waveform and it's FFT is shown in Fig. (8)



Fig(8) Current waveform of stator eccentricity fault at half-load

a) Line current waveform b) Corresponding FFT

Table 2 illustrates the positive, negative harmonics sequence and their amplitudes for different values of **v** at half-load, the data of the motor is:

Input Frequency	Motor Speed	Slip (s)
50Hz	2790 rpm	0.07

Table 2 Positive, negative harmonics at half –load (Eccentricity Fault)

v	Pos. Harmonic(Hz)	Amplitude(A)	Neg. Harmonic(Hz)	Amplitude(A)
1	980	0.023	880	0.063
3	1080	0.0597	780	0.06
5	1180	0.047	680	0.0513
7	1280	0.0156	580	0.043
9	1380	0.01	480	0.034
11	1480	0.026	380	0.0332
13	1580	0.01	280	0.051
15	1680	0.045	180	0.089
17	1780	0.0568	80	0.364
19	1880	0.026	0	0

C-Full-Load Test

This test involves operating the system at full-load, the values of current, speed and the slip are 8.5A, 2720 rpm and 0.093 respectively. The current waveform and it's FFT is shown in Fig. (9).

a)

b)

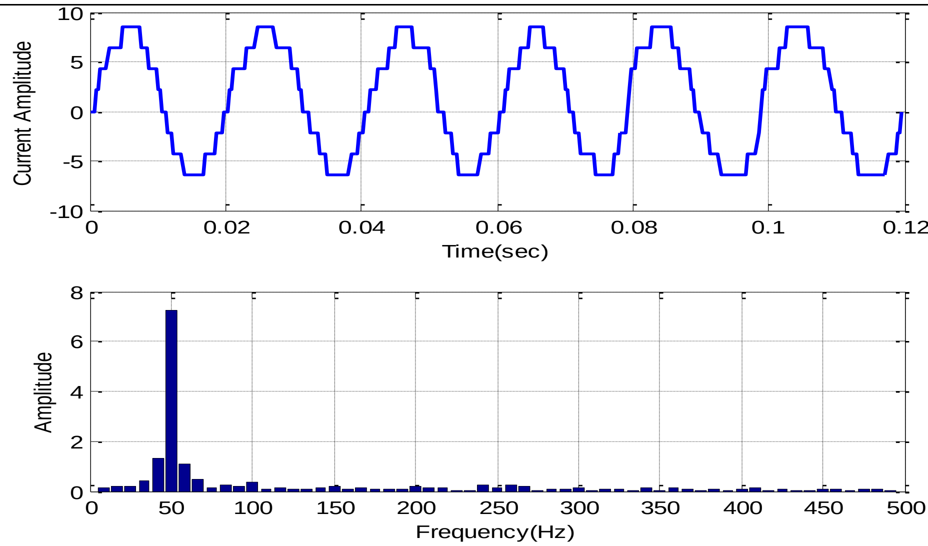


Fig. (9) Current waveform of eccentricity fault at full-load

a) Line current waveform b) FFT

Table 3 Illustrates the positive, negative harmonics sequence and their amplitudes for different values of v at full-load, the data of the motor is:

Input Frequency Motor Speed Slip (s) 50Hz
2720 rpm 0.093

Table 3 Positive, negative harmonics full-load (Eccentricity Fault)

v	Pos. Harmonic(Hz)	Amplitude(A)	Neg. Harmonic(Hz)	Amplitude(A)
1	957	0.0438	857	0.0323
3	1057	0.0445	757	0.027
5	1157	0.046	657	0.0334
7	1257	0.0319	557	0.082
9	1357	0.0466	457	0.0208
11	1457	0.022	357	0.066
13	1557	0.0115	257	0.157
15	1657	0.0155	157	0.086
17	1757	0.0131	57	0.673
19	1857	0.0212	0	0

*** Training of ANN for Faults Identification**

The current and speed signals acquire from a three-phase 2.2kW squirrel-cage induction motor. A software program was written using Matlab program package this program involve the fast Fourier Transform of the acquired data and the positive and negative harmonic frequency and their amplitudes. In order to make neural networks perform well, the data must be well-processed and properly-scaled before inputting them to ANN. Therefore there are two outputs corresponding to one fault and healthy condition. The number of neurons of hidden layer given to the program during the training process was two to give suitable error. The neural network being trained based on the amplitude of the side bands, a total of 120 data sets (20 data sets for the eccentricity fault condition) are used in the training. The type of network belong to supervised learning, it needs a teacher to lead it in order to achieve the determined goal. Fig. (10) illustrates the inputs and outputs of the ANN. In this research a feed-forward network is used, and it is trained with the back propagation algorithm using tan sigmoid function, pure line.

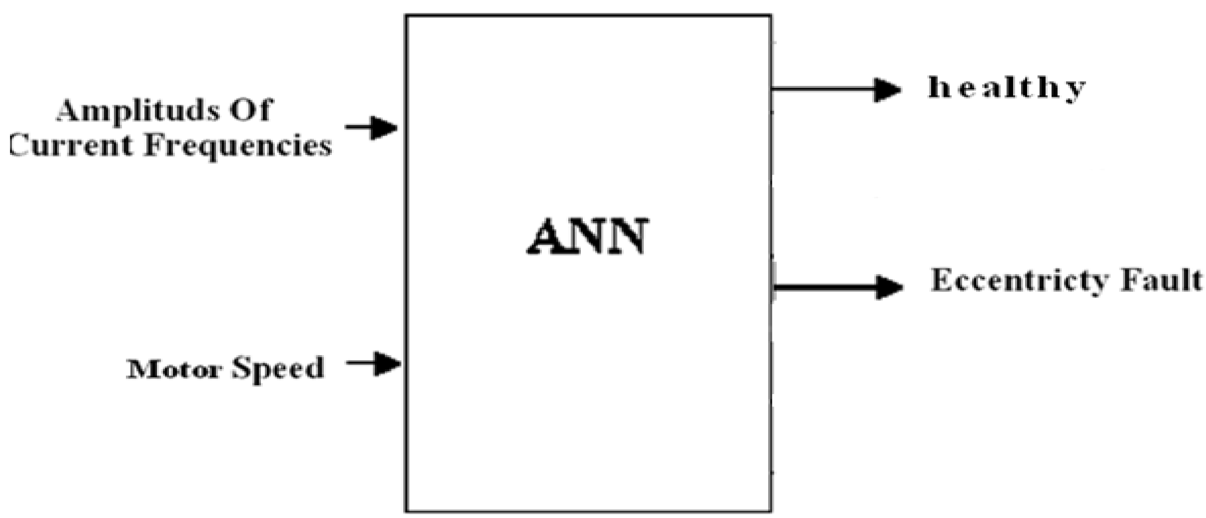
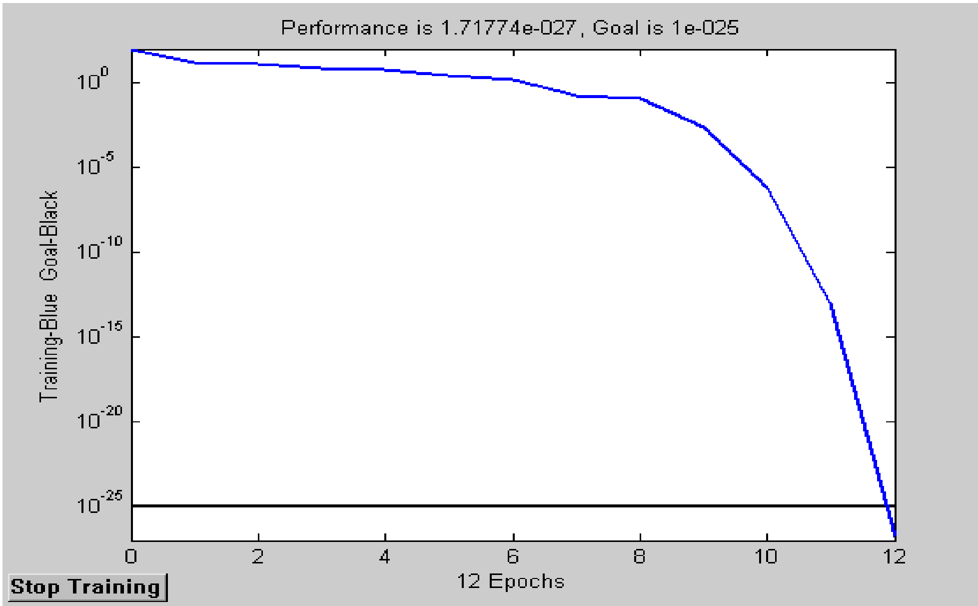


Fig. (10) Inputs and outputs of ANN



After

successful training the network, it will then used to detect the eccentricity fault. It is depicted training sum squared error related to the number of iterations in Fig. (11), the error of training parameter goal given to the program was (1e-25), but the result of the training was less than the error given to the program, as it is shown in Fig. (11).

Fig. (11) The performance of ANN Training

* CONCLUSION

The work reported in this paper has involved designing and building a motor monitoring system using an Aritificial neural network for fault detction of three phase induction motor .To accomplish this, a hardware system was designed and built to acquire three-phase stator current and speed from a (2.2kW) squirrel-cage induction motor. The ability of the phase current to detect specific fault was tested, since monitoring this parameter is the most convenient and cheapest way to sense a fault. it was clear that The sideband frequencies are function of the slip, so they are changing with the speed (that change with the load) . From the sideband frequencies calculated in the tables(1,2 and 3) it's found that the distance of the positive and negative from the fundamental increased with increasing of the load, and the same for different values of k/p and for all types of faults. From the reported work,the disadvantage of most ANN's are their inability to respond to previously unseen conditions. Therefore , if there is an occurance of a new fault that the network doesn't been trained to recognize ,and the fault may be misdiagnosed which produce weak output results.

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APPENDIX

(Motor Parameters):
2.2 KW (3HP), 2Pole, 50Hz, 380V

Rated Current ………. …………..........8.5A

Stator resistance (Rs)……………….…..2.302 Ω

Rotor resistance(R)………………….… 3.164 Ω

Rotor reactance (Xr)…………………..3.587 Ω

Stator reactance (Xs)…………………..4.265 Ω

Magnetizing reactance (Xm)……........90.919 Ω

Number of slots……………………………...24

Number of rotor bars…………………...……20