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Detection of Static Air-Gap Eccentricity in Three Phase induction Motor by Using Artificial Neural Network (ANN)

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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.
***Keywords* -** Static Eccentricity, Three Phase Induction Motor, Artificial Neural Network

Nomenclature Variables:

f	Main frequency
f_r	Vibration Frequency (in the current Spectrum)
f_y	Rotational Frequency
n_d	Eccentricity order
P	Pole pair
S	Slip
W_i	Weight of input
R	Number of rotor slots
v	Harmonics Index

I. INTRODUCTION

Rotating electrical machines play a very important role in the worlds Industrial life. In petrochemical and power utilities, the failure of electrical rotating machines, such as electric motors and generators cost millions of dinars. 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” approaching. So, the industry started investing heavily on preventive maintenance programs, that is, detecting machine problems before they can result in catastrophic failure [1].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..

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

a) Stator faults resulting in the opening or shorteing 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.
g) Bearing and gearbox failures.

From the above types of faults (a) the stator winding faults, (c) the broken rotor bar and end ring faults of induction machines, (e) the eccentricity related faults and (g) bearing faults are the most prevalent ones and thus demand special attention. Thus, these faults and their diagnosis techniques will be discussed briefly in the next chapter.

These faults produce one or more of the symptoms as given below:[2].

a) Unbalanced air-gap voltages and line currents.

b) Increased torque pulsation's.
c) Decreased average torque.
d) Increased losses and reduction in efficiency.
e) Excessive heating.

The diagnostic methods to identify the above faults may involveseveral 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.
g) Acoustic noise measurements.
h) Motor current signature analysis (MCSA).
i) 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 technique [2]. 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. Several authors have examined the effect of Bearing, stator phase and rotor eccentricity faults on machine parameters and performance. Different ways to model and to monitor the machines with Bearing, Broken rotor bar, Stator inter turn and air-gap eccentricity faults have been developed.

C.Tassoin et al. [3] have presented the detection of broken rotor bar for large induction motors by selecting the line current, voltage and speed as the monitored parameters. However , they proposed a new way for modeling the machine under broken bar .**R.R.Schoen et al.** [4] have also proposed new method for induction motor fault detection by built on_line system utllizes artificial neural networks to learn the spectral characteristics of a good motor operating on_line**.**

S. Liling et al. [5] have reported an improved stator current based detection scheme for bearing fault in induction motors, by experiments of bearing fault then thoroughly analyzing the experiment results.

M. S. Arefeen et al. [6] 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.

H. A. Toliyat [7] used spectrum analysis of machine line current (Motor Current Signature Anaylsis) to detect broken bar faults. He investigate the side band components, f_b ,around the fundamental for detecting broken bar faults.

H. A. Toliyat et al. [8] 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. The interest in the condition monitoring, on-line and/or off-line, of ac machines has increased tremendously in the last few years because of economic pressures, smaller profit margins and high costs of replacement and spare parts.Therefore, to achieve this goal, it is very important to be able to develop simple models for the machines under fault conditions and then analyze the effect of faults on the machines' behavior.

B.Ayhan et al. [9] described two fault-detection schemes for a broken –rotor bar fault detection with a multiple signature –processing and demonstrates that the multiple signature processing is more efficient than a signal signature processing

M. J.Devaney et al.[10] used the anlysis of the vibration signal to detect the motor Bearing faults using Fourier transform (FT) the magnitudes of the characteristics faults frequncies are compared with base-line values to detect any deterioration in bearing health**.**

S. Nandi et al. [11] claimed that although MCSA can detect harmonics as potential indicators of a fault in the stator winding, it was claimed that these harmonics can be unambiguously detect at the terminal voltage **.**

Yazidi et al.[12] observed that the techniques relying on the stator winding current analysis are not always reliable, especially when the number of shorted turns is small compared to the to the total number of turns in a phase winding.

A. Siddique et al.[13] They their focus his review of various AI techiques to the iduction motors, more specifically to the stator winding fault detection.

X. Huang et al.[14] 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 relashionship and estimate corresponding signature amplitudes over a wide range of operation conditions.

F. Filippetti et al.[15] 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 distingush between "healthy"and "faulty"machines.The aim of this Paper is to:

1- Use a combination of two techniques, namely motor current signature analysis togather with neural network to study the effect of faults .

2-Training the neural network to simulate the effects of three types of 3-phase induction machine faults.The required training data which will be used to train the ANN are obtained pratically by the designed monitoring system.

3-Testing or studying the effects of eccentricity faults by using induction machine current signature. The rest of this paper is structured as follows. Section II Eccentricity Related Faults and the experimental set-up and mathematical description of the eccentricity fault problem. Section III provides experimental results., Section IV Eccentricity Related Faults Test, section V illustrates Training of ANN for Faults Identification ,section VI provides the conclusions and the future work.

II. ECCENTRICITY RELATED FAULTS AND THE EXPERIMENTAL SET-UP

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.

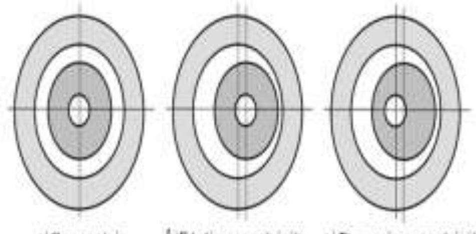

Fig. (1) Eccentricity types

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 is: [1]

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

I. where n_d**=0** in case of static eccentricity, and n_d **=1,2,3,…** and 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, $\mathbf{k_1}$ 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],

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

II. 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).

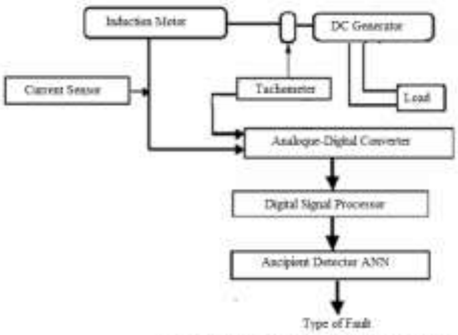

Fig 2. The Experiment Set For Fault Detection of Induction Motor

The inputs to the data acquisition are from one of motor line current and from the tachometer; 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 (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 obtain the sampling frequency and sampling time of the waveform. The speed of the motor measured by using the tachometer the value of the speed will convert 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 as illustrated in the tables, these amplitudes will used to train the neural network to give the incipient detection of the fault. As mentioned before there are two types of eccentricity dynamic and static. In this experiment the static eccentricity was tested on motor in which the center of rotor was not at the center 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 used to

Fig. Side view of rotor eccentricity motor

III. EXPERIMENAL RESULTS

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

III. 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 its FFT is shown in Fig. (3).

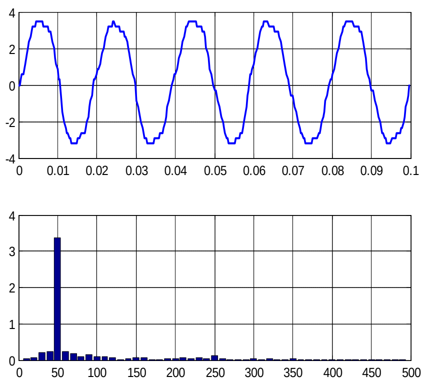

Fig. (3) Current waveform in healthy motor at no-load

a) Line current waveform b) FFT

II. B. Half-Load Test

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

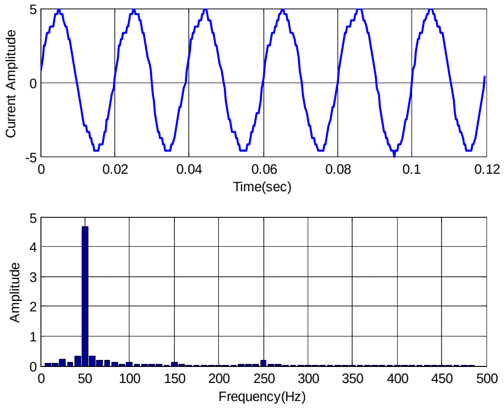

Fig. (4) Current waveform in healthy motor at half load

a) Line current waveform b) FFT

III. C. Half-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 shown in Fig. (5).

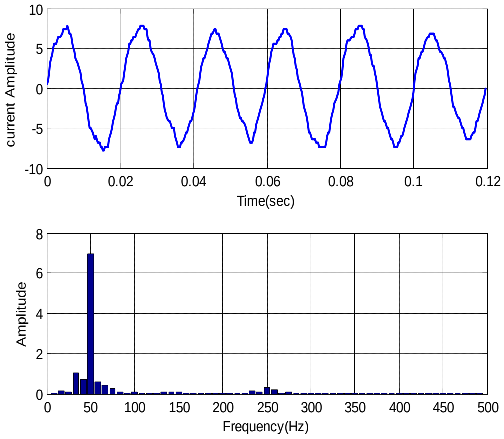

Fig. (5) Current waveform in healthy motor at half-load

a) Line current waveform b) FFT

IV. ECCENTRICITY RELATED FAULTS TEST

The second experiment was eccentricity fault as mentioned before. That there are two types of eccentricity dynamic and static. In this experiment the static eccentricity was tested on motor in which the center of rotor was not at the center 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 used to calculate side bands frequencies for three cases.

IV. B. No-Load Test

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

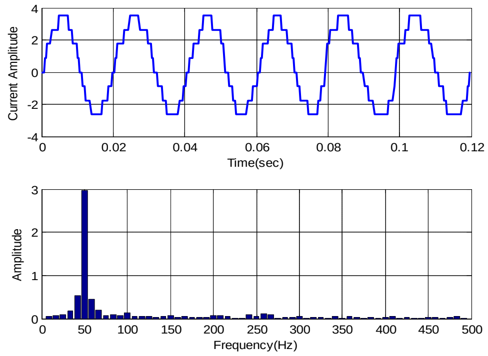

Fig. (7) Current waveform of eccentricity fault at no-load

a) Line current b) FFT

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

Input Frequency Motor Speed Slip (s) $\boldsymbol{n_d}$ **R(□)**

50Hz 2810 rpm 0.063 0 20

Equation (1) is used to calculate the positive and the negative harmonics and their amplitudes.

Table1 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
1	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

IV.B. Half-Load Test

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

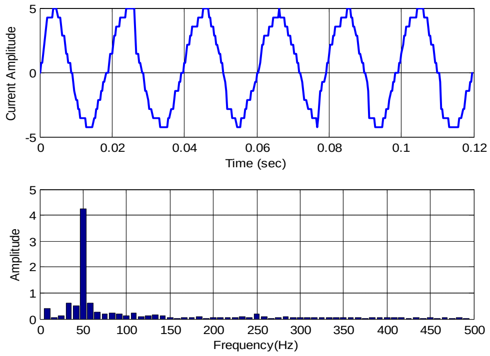

Fig. (8) Current waveform of stator eccentricity fault at half-load

a) Line current waveform b) 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) n_d **R** (Ω)
50Hz 2790 rpm 0.07 0 20

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	0.056	580	0.043
9	1380	0.01	480	0.034
11	1480	0.026	380	0.0124
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

IV.C. Full-Load Test

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

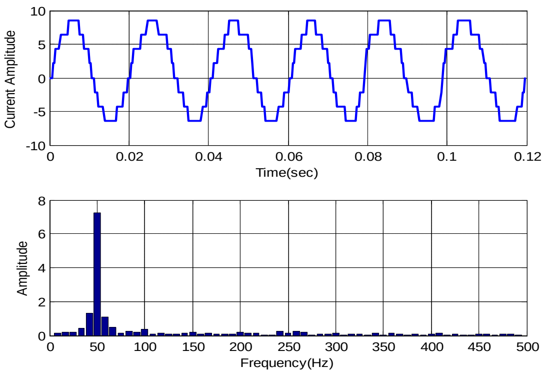

Fig. (9) Current waveform of eccentricity fault at full-load

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) n_d ***R*** (Ω)
50Hz 2720 rpm 0.093 0 20

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	0.151
15	1657	0.0155	157	0.086
17	1757	0.0131	57	0.673
19	1858	0.0212	0	0

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

V. TRAINING OF ANN FOR FAULTS IDENTIFICATION

The current and speed signal acquire from a 2.2kW squirrel-cage, three-phase induction motor. A software program was written using Matlab program package this program involved 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 2 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.

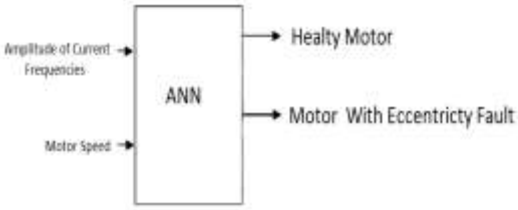

Fig. (10) Inputs and outputs of ANN

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).

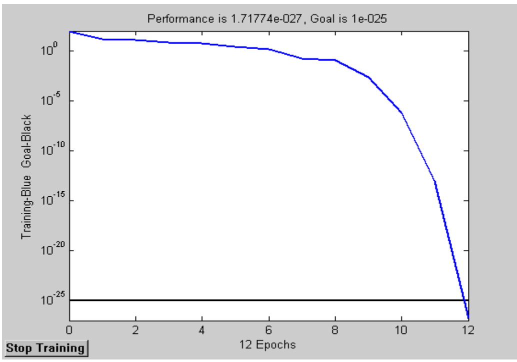

Fig. (11) The performance of ANN Training

Fig.(12) illustrates the control panal of the programs, it consist of five steps as shown above . In step 1 the type of the test slected , in step 2 the data was loaded The fast fourier transform and the side bands calculation controled by steps 3, 4 respectively , step 5 will give the type of fault

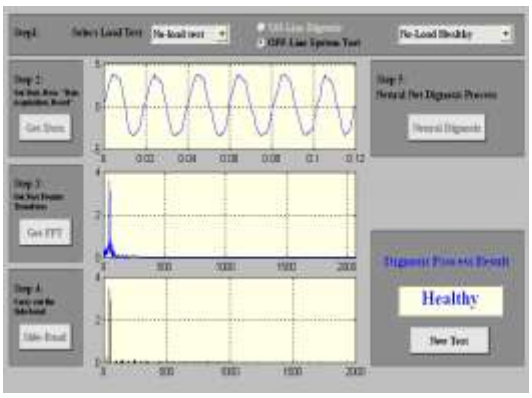

Fig. 12. Control panel of the neural network diagnosis programs

In Figs.13, 14, and 15 the no-load,half –load and full-load in Healthy case were chosen as example, in fact the total number of cases was (6) three cases in eccentricty fault , these cases will be demonastrated in this paper for example the half-load in case of healthy will be chosen the type of test should be changed to half load test, and changed to full –load test for full-load detection.

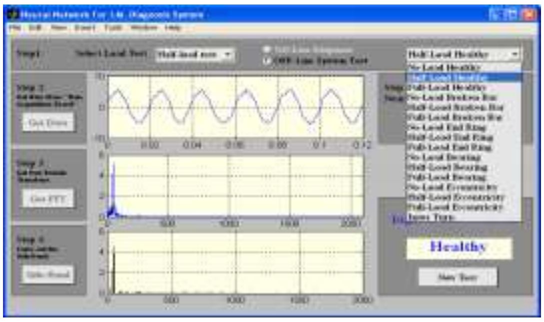

Fig.13. Derection of healthy motor at full –load

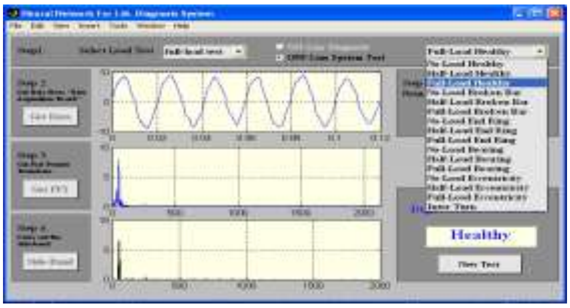

Fig.14. Derection of healthy motor at full –load

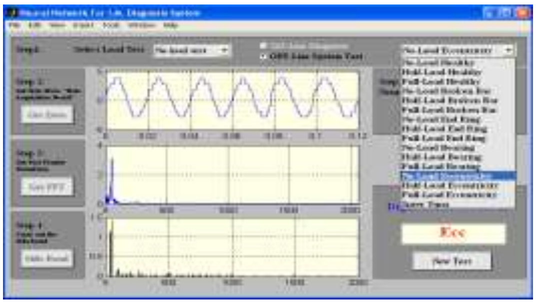

Fig.15 Detection Of Motor with eccentricty fault motor at No-Load

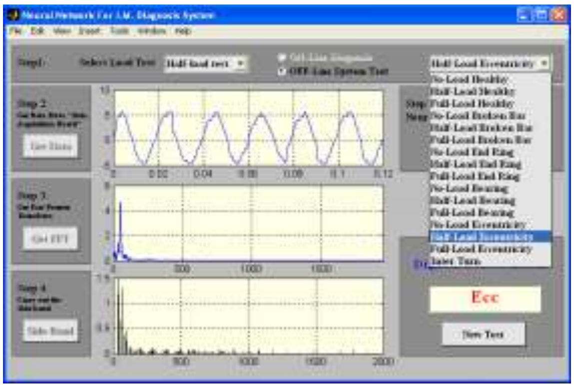

Fig.16. Derection of Motor with eccentricty fault motor at Half –load

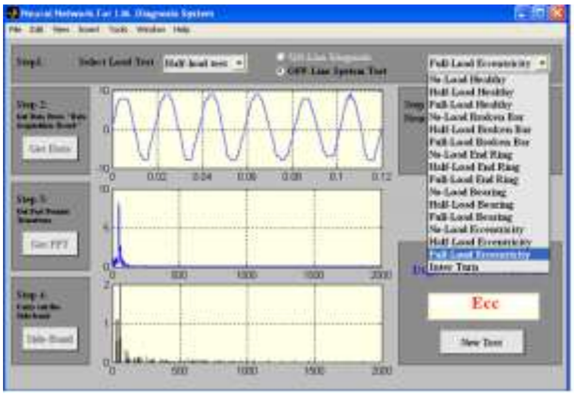

Fig.17. Derection of Motor with eccentricty fault motor at Half –load

VI. CONCLUSION AND FUTURE WORK

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 train to recognize ,and the fault may be misdiagnosed which produce weak output results. The number of selected input channels of data acquisition circuit used in this work was two (one for current and the other for tachometer), these slected chanals may increase to four depend on the types of data needed to investigated.

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Appendix A

(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