Bispectrum Analysis of Motor Current Signals for Fault Diagnosis of Reciprocating Compressors

Abdelhamid Naid

a.naid66@yahoo.com

Abstract. The induction motor is the most common driver in industry and has been previously proposed as a means of inferring the condition of an entire equipment train, predominantly through the measurement and processing of power supply parameters. This has obvious advantages in terms of being non-intrusive or remote, less costly to apply and improved safety. This paper describes the use of the induction motor current to identify and quantify a number of common faults seeded on a two-stage reciprocating compressor. An analysis of the compressor working cycle leads to current signal the components that are sensitive to the common faults seeded to compressor system, and second- and third-order signal processing tools are used to analyse the current signals. It is shown that the developed diagnostic features: the bispectral peak value from the amplitude modulation bispectrum and the kurtosis from the current gives rise to reliable fault classification results. The low feature values can differentiate the belt looseness from other fault cases and valve leakage and inter-cooler leakage can be separated easily using two linear classifiers. This work provides a novel approach to the analysis stator current data for the diagnosis of motor drive faults.

1. Introduction

Induction machine stator current signals have been used widely to determine the health of the induction machine since the early 1980's [1]. A limited amount of work has been undertaken in using the current signals to investigate the potential of using the induction machine as a means of assessing the condition of downstream driven equipment. In [2] it was shown that the influence of mechanical problems that result in rotor disturbances can be detected due to changes in the induction machine stator current, and in [3], it was shown that the induction machine stator current can be used to detect the presence of load imbalance. In [4] a large-scale test involving the on-line monitoring of 120 induction machines in a coal preparation plant using supply parameters was presented. The outcomes were sufficiently promising to suggest that there are serious opportunities for the techniques to be exploited, especially using the effective negative sequence impedance.
Further, it has been shown that the induction machine supply current can contain components related to abnormalities in equipment such as compressors, pumps, rolling mills, mixers, crushers, fans, blowers and material conveyors[5] and the technique has been used to detect specific axial flow compressor problems [6]. It has also been found that worm gear tooth meshing frequency components of gearboxes are present in the supply current spectra [1] of the driving induction machine. In all these publications, the use of the motor supply parameters for the detection of equipment train faults has been limited in that no deterministic approaches have been demonstrated. One of the main reasons for this lack of diagnostic clarity is that the harmonic content and noise contained within an induction machine supply parameter,

and in particular the stator current, is high and that traditional two-dimensional spectral analysis techniques can be insufficient to properly correlate the stator current data with faulted conditions.

Higher Order Spectra (HOS) are signal processing tools that have shown [7-8] significant benefits over traditional, two dimensional spectral analyses because of non-linear system identification, phase information retention and Gaussian noise elimination properties. The application of HOS techniques in condition monitoring has been variously reported with [9] and [10] being representative examples and it is clear that multi-dimensional HOS measures can contain more useful information than traditional two-dimensional spectral measures for diagnostic purposes. Further, in [10], it was shown that these measures could be used in a deterministic manner to predict the HOS components of induction machine vibration sensitive to a number of fault conditions. Additionally, it was demonstrated that the HOS measures were more sensitive to the fault conditions than traditional spectral analysis. However, these techniques have not been extended to include induction machine supply parameter investigations or faults on the downstream driven equipment train. This paper begins to address these issues by investigating the capability of the induction motor phase current to detect different faults in a reciprocating compressor. Theoretical principles are presented that predict the frequency components of the motor phase current sensitive to the seeded faults. An experimental investigation is presented and four compressor conditions are investigated over a wide range of discharge pressure conditions. The bispectrum signal processing tools are then used to investigate the predictive phase current frequency components' capabilities to detect both the presence and magnitude of the seeded faults.

2 Characteristics of Motor Current Signals

Reciprocating compressors are common equipment in industry. A compressor system consists of typically an induction motor, a belt transmitter and a multi-cylinder compressor. The compressor has two basic working processes: compression and expansion. From previous study [11], during the compression it needs more power while the expansion needs less power. This working process will give rise to a periodically varying load to the driving motor. The speed of the motor is then varying accordingly. From the motor drive theory, the speed variation will lead to corresponding changes in the current fed to the motor[12]. When a compressor runs under normal conditions, the fluctuation increases with the increase of discharge pressure and is valued in a pre-designed range.

This means that the measured current signals are also changes with the fluctuations. Because of the speed fluctuation, the signals exhibit different forms of modulations including amplitude modulation and angle modulation. The degree of the modulation is determined by the amplitudes of the load fluctuations.

Therefore, if there is a fault from the compressor, the load fluctuation will be changed and hence the modulation is different. Various leakages in inter-cooler, piston rings, etc. may reduce the fluctuations and hence reduce the modulations whilst some faults such as valve leakages and blockages may increase the fluctuations and hence cause a high degree of modulations. This then can be used for fault detection. From previous researches such as [12-13] the modulations will exhibit a series of sidebands f_{sb} at the supply frequency in a motor current spectrum.

$$f_{sb} = f_s \pm mBf_r \qquad\qquad (1)$$

where f_s is the supply frequency, m=1, 2, 3, ... etc., B is the belt transmission ratio and f_r is the rotor rotational speed. Fig1. shows the current signals from a two-stage reciprocating compressor. The compressor has a 3kw three-phase four-pole induction

motor, a belt with a transmission ratio of 3.1 and a two-stage compressor operating in a pressure range from 80psi to 120psi (5.5bar to 8.3bar). From the in-cylinder pressures and compressor torques, shown in Fig. 1(a) and (b), respectively, the motor is under a dynamic load fluctuating according to the working cycle of the compressor. This fluctuating load leads to a modulated current waveform, shown in Fig. 1(c). The current waveforms exhibit clear amplitude modulation in-line with the torque waveforms. The spectra of current signals, shown in Fig1.(d), exhibits typical amplitude modulation(AM) features. They are dominated by the carrier components at the supply frequency 50Hz and also show clearly the sideband components at 50±7.3Hz which correspond to the operating frequency of the compressor.

More interestingly, the amplitude of the current waveform from the valve leakage seems slightly lower than that of healthy condition. In the spectra, the sideband amplitudes for the leakage are also slightly higher while the supply amplitude has a small decrease when compared with the spectrum of the healthy condition. These are consistent with the changes in the pressure and torque graphs, which mean that the current signals contain sufficient information for compressor fault detection and diagnosis.

However, a compressor usually operates in a wide range of discharge pressures. The changes due to operating pressures may mask the small changes due to faults, which makes it difficult to separate different types of faults. In addition, different types of compressors faults may also produces similar change patterns in both the spectra and the waveforms. These means that the second-order analysis is not sufficient to discriminate the changes and hence more advanced signal processing methods have to be used to enhance the small changes for separating different types and severities of the compressor faults.
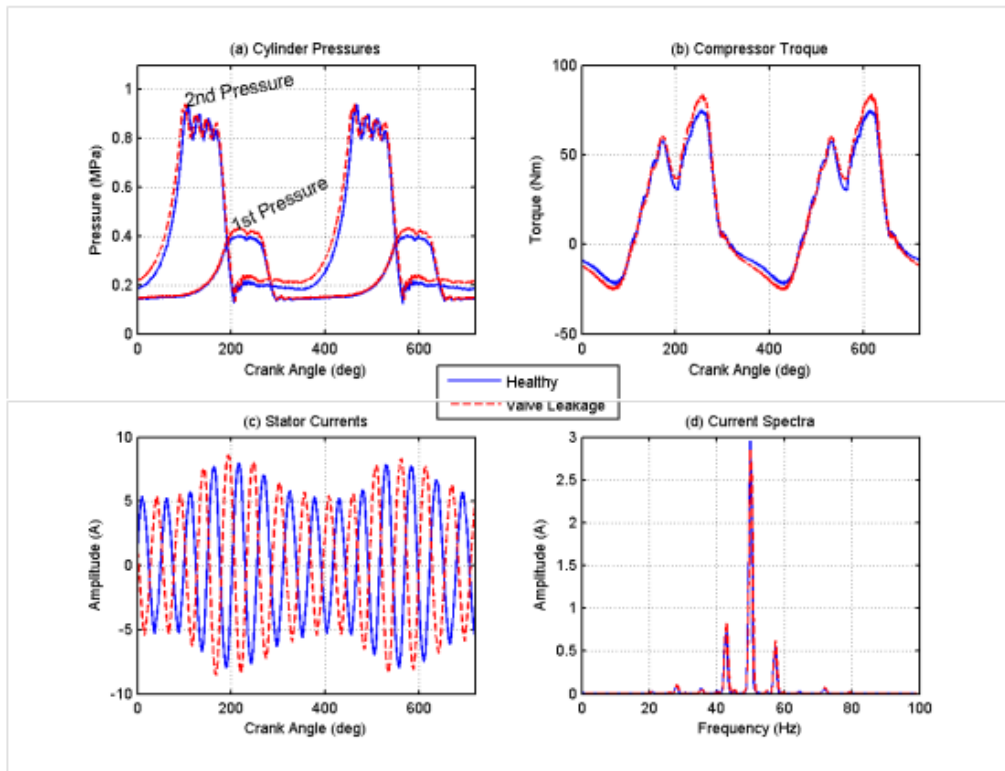

Fig. 1 Stator current waveforms and spectra for a healthy compressor and a valve leakage case

3 Conventional Bispectrum

Conventional bispectrum analysis has a number of unique properties such as non-linear system identification; phase information retention and Gaussian noise elimination when compared with common spectrum analysis. To develop more effective diagnostic features, bispectrum analysis is applied to the current signals to extract and study possible non-linear characteristics under different operating conditions and fault cases.

Given a discrete time current signal $x(n)$, the discrete Fourier transform (DFT), $X(f)$, of $x(n)$ is defined to be

$$x(f) = \sum_{n=-\infty}^{\infty} x(n)e^{-2jm} \tag{2}$$

and the well-known second-order measure, the power spectrum of $x(n)$ is obtained by the expression

$$P(f) = E[X(f)X^*(f)] \tag{3}$$

where $X^*(f)$ is the complex conjugate of $X(f)$ and $E[\ ]$ is the statistical expectation. The power spectrum is a linear transform and is a function of the frequency index f. Extending these definitions to measures of order 3 gives rise to the bispectrum $B(f_1, f_2)$ which is defined as

$$B(f_1, f_2) = E[X(f_1)X(f_2)X^*(f_1 + f_2)] \tag{4}$$

where f_1, f_2 and f_1+f_2 are the individual frequency components obtained for the Fourier series integral. Note that, unlike second-order measures, this third-order measure is a complex quantities in that it contains both magnitude and phase information about the original time series $x(n)$. The bispectrum can detect the presence of Quadratic Phase Coupling (QPC). QPC occurs when the phases of the frequencies f_1, f_2 and f_1+f_2 sum to zero i.e. $\emptyset_{f1} + \emptyset_{f2} - \emptyset_{f1+f2} = 0$ and this is indicated by a peak in the bispectrum at the *bifrequency $B(f_1, f_2)$* and when the associated *biphase, $\Phi(f_1, f_2)$*, tends to zero.

Fig. 2 shows the bispectra of the current signals for a healthy compressor and a valve leakage case. The healthy bispectrum show a major QPC peak at bifrequency (50, 50) and a number of small peaks which are separated by a frequency interval of 7.3Hz. These components are clearly relating to the compressor working process. Similarly, the bispectrum for the faulty case also have the major QPC peaks but with less small peaks. Comparing between these two bispectra, it is seen that the major peak of the faulty case is lower and the two peaks close to the major peak are higher. The change amplitude is clearly larger than that from the second-order spectrum in Fig.1. This shows that this third-order based bispectrum can produce more discriminatory information than the second-order methods.
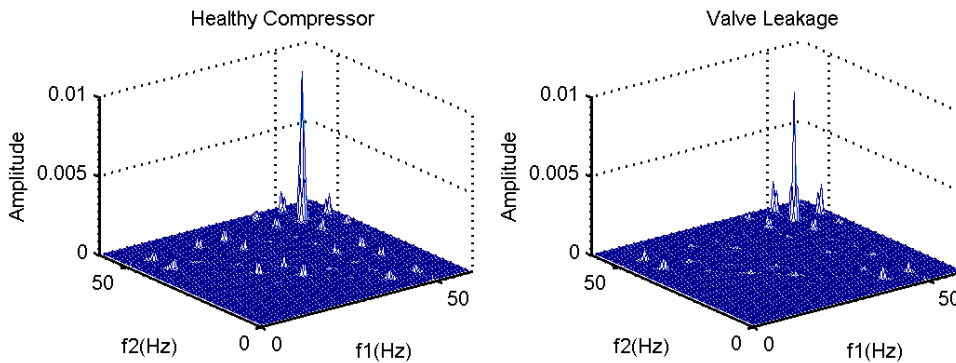

Fig.2 Conventional Bispectra for a healthy compressor and a valve leakage at 120psi

However, too many small QPC peaks in the conventional bispectrum may lead to confusions in interpreting the results. The major components at (50, 50) seems from the coupling between 50Hz, 50Hz and 100Hz. However, there are is very low amplitude at 100Hz due to spectrum leakage.

Thus this (50, 50) component may be a false QPC. Apart from this 50Hz peak, other peaks are the compiling from the components relating to compressor system: working frequency 7.3Hz, supply frequency 50Hz, sidebands of 50±7.3Hz and sidebands harmonics. However, amongst these components, only the small peak at (7.3, 50) is useful to show the two independent components: 7.3Hz and 50Hz in the AM current signal and others may be redundant.

In addition, so many of the peaks make the diagnostic feature extraction more difficult. Generally, more evaluation effort is required to determine the optimal from when a large number of candidates are involved.

4 Amplitude Modulation Bispectrum

Equation (4) examines only the presence of QPC from the harmonically related frequency tripe (f_1, f_2, f_1+f_2) and overlooks the possibility that the occurrence of (f_1-f_2) may be also so due to the QPC between f_2 and f_1. Because of this it is not accurately enough to analyses AM signals such as the motor current signals. To improve the performance of the Bispectrum in describing the motor current signals, a modified Bispectrum, named an AM Bispectrum is defined [14-15] as

$$B_{AM}(f_1, f_2) = E[X(f_2 + f_1)X(f_2 - f_1)X^*(f_2)X^*(f_2)] \qquad (5)$$

Equation(5) now takes into account both (f_1+f_2) and (f_1-f_2) simultaneously for possible QPC in AM signals. It shows[15] that a bispectral peak will appear at bifrequency $B_{AM}(f_1, f_2)$ if ($f_2 + f_1$) and ($f_2 - f_1$) are both due to QPC between f_1 and f_2. This is more accurate in representing the feature of the AM signal.

Figure 3 shows the AM bispectra for the two signals show in previous section. There is only a clear peak at bifrequency (7.3, 50). This shows that the sidebands and the supply frequency have a single QPC, leading to a more clear and concise representation of the AM current signals, which makes the extraction of fault detection straightforward. More importantly, the peak amplitude for the valve leakage is more than 30% higher than that of the healthy case, which can be directly used as an important feature to detect the presence of the valve fault.
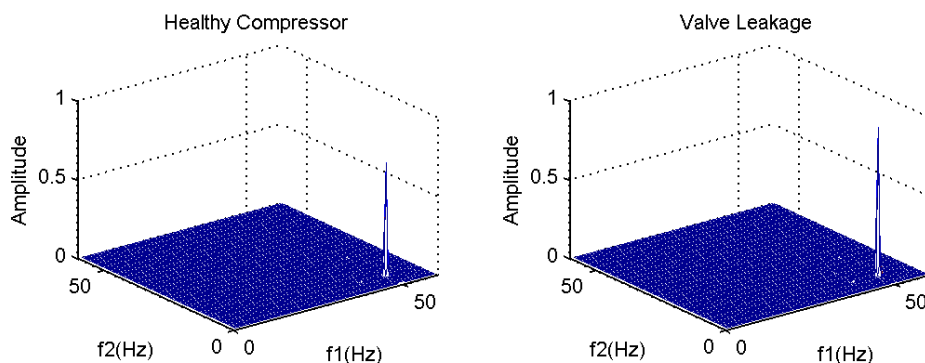

Fig3. AM Bispectra for a healthy compressor and a valve leakage case at 120psi

5 Bispectrum Based Diagnosis

The peak amplitudes from bispectra are very sensitive to the spectrum leakage. Rather using the peak values directly for separating different faults, an average value A_B

around the peak is used for fault separation, which is defined in the bispectrum domain as

$$A_B = \frac{1}{4K}\sum_{j=m-k}^{j=m+k}\sum_{i=n-k}^{i=n-k}A_{ij} \tag{6}$$

Where (m, n) is the index of the peak position; $k=4$ is the number of the spectral lines around peak (m, n). To reduce the influence that the amplitude of current signals increases with compressor discharge pressures, the average bispectrum amplitude is normalised by the root mean square (RMS) value I_{rms}:to obtain a more reliable bispectrum peak feature:

$$A_{Bn} = \frac{A_B}{I_{rms}} \tag{7}$$

Obviously, a higher value of A_{Bn} shows a higher degree QPC in the signal. In addition, for a complete separation of the seeded faults, kurtosis values of the current signals are also calculated by

$$K = \frac{1/n\sum_{i=1}^{i=n}(x_1-x)^4}{[1/n\sum_{i=1}^{i=n}(x_1-x)^2]^2} \tag{8}$$

The benefit of using signal kurtosis is that it highlights more the high amplitudes of the AM signals and produce better fault separation when compared to the second-order measures such as peak factor.
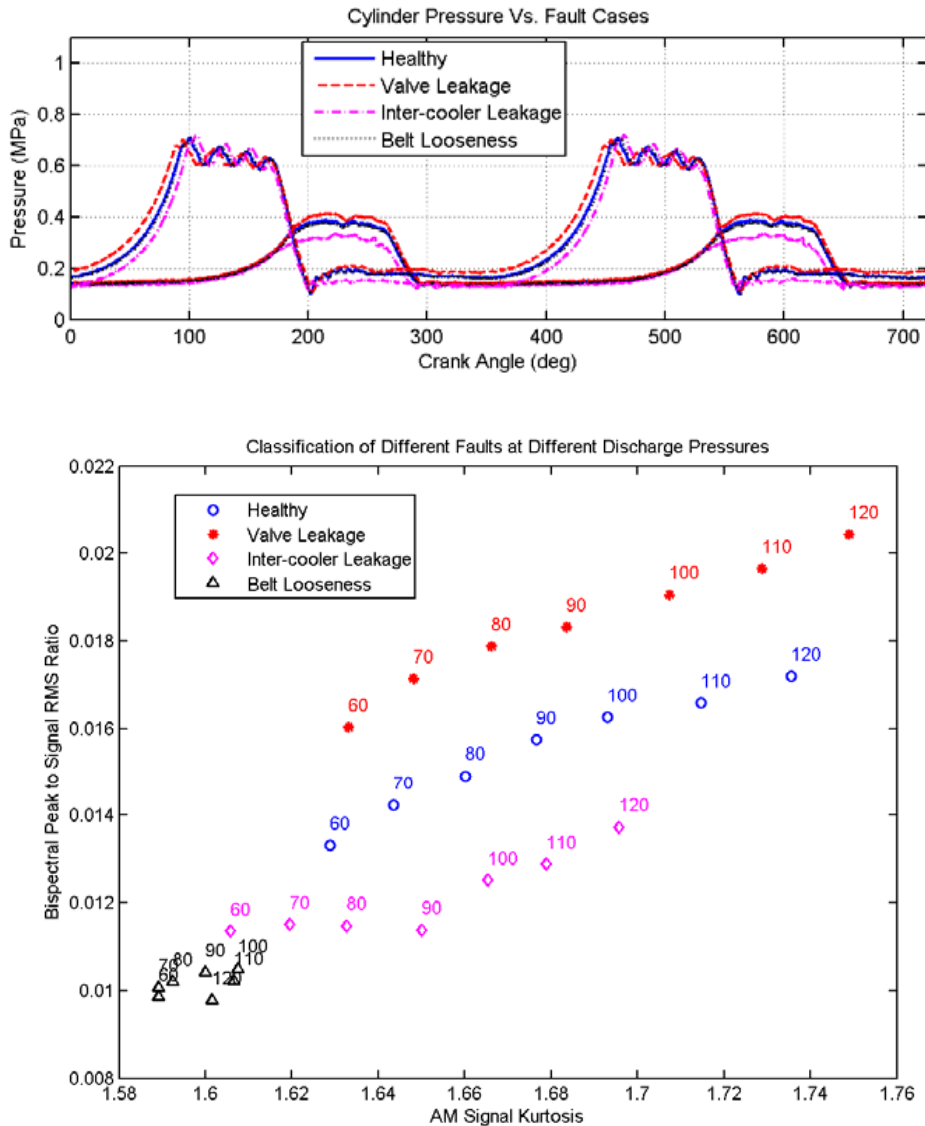

Fig. 4 Performance of compressors fault classification

Fig. 4 shows the performance of compressor fault separation based on the bispectrum peak features and signal kurtosis. The top graph shows the effects of the three common faults: valve leakage, inter-cooler leakage and belt looseness, on the cylinder pressures. The valve leakage causes a slight increase in the pressures of both the first stage and the second stage cylinders whereas the intercooler creates a small decrease in the pressures. However, the belt looseness does not cause any changes to the cylinders pressures. This means that any cylinder pressures based detection methods such as pressure, vibration and temperature will failure in detecting this type of fault. In addition, these three seeded faults are very small. The compressor can produce the required pressure without noticeable changes in its service performance.

However, the suggested diagnostic features, shown in the bottom plots of Fig. 4, show clear differences between different fault cases and from the healthy operation. In addition, the differences spread over a wide range of discharge pressures (80psi to 120psi) which is the rated range of the compressor. The valve leakage produces higher values of both the bispectral peak and the signal kurtosis whereas the inter-cooler leakage shows lower values for both the features. This is consistent with the changes in cylinder pressures and the load torques. From this it can be concluded that either too high or too low feature values will indicate that a faulty or abnormal operation. In particular, the belt looseness, like the low discharge pressure operations, has very low feature values, which shows the abnormal compressor operation.

Based on above discussions, compressor fault diagnosis can be carried out at its rating operation range from 80psi to 120psi. The low feature values can be used to differentiate the belt looseness from other fault cases. Valve leakage and inter-cooler leakage can be separated easily using two linear classifiers.

6 Conclusions

This work has clearly shown that the bispectrum analysis of the induction motor current clearly has significant potential as a means of non-intrusively detecting the presence of incipient faults in its driven equipment items. From compressor working process it related the changes in the incylinder pressure to the motor current amplitude modulation. However, the conventional Bispectrum is not so effective in analysing the AM current signals for feature extraction. A modified Bispectrum i.e. AM bispectrum is then used to obtain a more distinctive QPC peak of the AM current signals.

An averaged QPC peak in conjunction with signal kurtosis is then developed to diagnosis different compressor faults including valve leakage, inter-cooler leakage and belt looseness. The classification results shows that the low feature values can be used to differentiate the belt looseness from other fault cases and valve leakage and inter-cooler leakage can be separated easily using two linear classifiers.

References

[1] W. T. Thomson, M. Fenger, "Current signature snalysis to setect induction motor faults", IEEE Ind. Appl. Mag., Jul./Aug. 2001, pp26-34.
[2] M. E. H. Benbouzid, "A review of induction motors signature analysis as a medium for faults detection", IEEE Trans. Ind. Elec., Vol. 47, No. 5, Oct. 2000, pp 984-993.
[3] R. R. Obaid, T. G. habetler, R. M. Tallam, "Detecting load unbalance and shaft misalignment using stator current in inverter-driven induction motors", IEEE int. Elec. Mach. And Drives Conf., pp1454-1458, 2003.

[4] G. T. Honce, J. R. Thalimer, "Reducing unshceduled plant maintenance delays – field test of a new method to predict electric motor failure", IEEE Trans. Ind. Appl., Vol. 32, No. 3, May/Jun. 1996, pp689-694.

[5] R.C. Kryter, H.D. Haynes, "Condition monitoring of machinery using motor current signature analysis", Sound & Vib., Sep. 1989.

[6] K. N. Castleberry, S. F. Smith, "A dedicated compressor monitoring system employing current signature analysis", ORNL report DE 93010270.

[7] H. Fanglin, G. Songnian, "Application of higher order cumulant to structure fault diagnosis", Proc. 11th Inter. Mod. Anal. Conf., pp1237-1240, 1993.

[8] G. Gelle, M. Colas, G. Delaunay, "Higher order statistics for detection and classification of faulty fan belts using acoutical analysis", IEEE Sig. Proc. Workshop on HOS, 21-23 Jul., 1997.

[9] I. M. Howard, "Higher-order spectral techniques for machine vibration condition monitoring", Proc. Instn. Mech. Engrs., Vol. 211, Part G, pp211-219, 1997.

[10] N. Arthur, J. Penman, "Induction machine condition monitoring with Higher Order Spectra", IEEE Trans. Ind. Elec., Vol. 47, No. 5, pp 1031 – 1041, Oct. 2000.

[11] M. Elhaj, F. Gu, A.D. Ball, A. Albarbar, M. Al-Qattan, A. Naid, "Numerical Simulation and Experimental Study of a Two Stage Reciprocating Compressor for Condition Monitoring" Mechanical Systems and Signal Processing, Vol.22 pp.374-389, Aug. 2007.

[12] R. Schoen, T. Habetler, "Motor bearing damage detection using stator current monitoring", IEEE transaction on Industry application vol. 3 No. 6 November/Dec. 1995.

[13] Schoen R.R. and Habetler G. T "Effects of time varying loads on rotor fault detection in induction machines". IEEE Transaction on Industry Application Vol 31 No. 4 July/August 1995.

[14] I. I. Jouny and R. L. Morese, "Bispectra of modulated stationary signals", IEE. Electronics Letters, Vol.30, No. 18, 1994, pp. 1465-1466

[15] J.R. Stack, R.G. Hartley and T.G. Habetler, "An amplitude modulation detector for fault diagnosis in rolling element beatings", IEEE Transactions on Industrail Electonics, Vol. 51, No. 5, pp. 1097-1102, 2004.