REVIEW OF CONDITION MONITORING IN ELECTRICAL MACHINES: STRATEGIES AND TECHNIQUES

Ali Salah Hennache
Hail College of Technology, P.O. Box 1690, Hail, Kingdom of Saudi Arabia.

ABSTRACT

The problems of anomalies and failures of electrical machines have frequently lead to loss of production, high maintenance and operation costs. As the capital cost of modern machines is very high, the requirement of continuous and prolonged operation becomes inevitable, to sustain economic operation. There has been a trend towards adoption of various forms of condition monitoring to know the deteriorating condition of a machine component, well in advance of a breakdown, for proactive maintenance which contribute to better health of electrical machines, reduced maintenance costs, efficient use of personnel and improved system efficiency. These problems have been the subject of several pieces of research, the reason being the possibly serious consequences already mentioned.

At present an on-line monitor may be relatively simple and require the back-up of more sophisticated and expensive equipment should the need arise, but with the appearance of relatively cheap microprocessors it is possible to foresee the use of powerful on-line monitoring, certainly in large base-load power stations and in smaller machines performing critical tasks. Such processors could gather and analyze the output of a variety of probes and sensors

To obtain an accurate measure of the condition of machinery, a wide range of approaches can be employed to extract features indicative of condition. By comparing these features with features for known normal and probable fault conditions, the machine's condition can be estimated. The approaches used vary from measuring vibrations, which yields signals often requiring a significant amount of processing. Other approaches include monitoring torque, acoustic emission, speed, electrical currents and voltages, temperature and system input/output relations.

The purpose of this paper is to briefly review the different types of faults (electrical and mechanical) and the strengths and weaknesses of different monitoring methods and diagnostics schemes , and then to present new alternatives which could be used to significantly enhance existing monitoring systems. This paper can also be used as a very simple clear guide to new researchers in the area of monitoring and diagnosing electrical machines.

1. Introduction

The monitoring of the condition of machinery can significantly reduce the costs of maintenance. Firstly it can allow the early detection of potentially catastrophic faults which could be extremely expensive to repair. Secondly it allows the implementation of condition based maintenance rather than periodic or failure based maintenance. In these cases significant savings can be made by delaying scheduled maintenance until convenient or necessary.

To obtain an accurate measure of the condition of machinery, a wide range of approaches can be employed to extract features indicative of condition. By comparing these features with features for known normal and probable fault conditions, the machine's condition can be estimated. The approaches used vary from measuring vibrations, which yields signals often requiring a significant amount of processing, to oil debris analysis where the metal worn off the machine can be analyzed. Other approaches include monitoring acoustic emission, electrical currents, temperature and system input/output relations.

It is thus, very important that the distinction between monitoring and protection is highlighted. Protection is generally installed to intercept criticalities as quickly as possible after they occur. Monitoring should be designed to pre-empt such occurrences and give an early indication of the onset of possible malfunctions.

A survey [1] of all published work on condition monitoring cannot be reviewed in this paper, and so the general methods will be broadly categorized and only those major methods used with electrical machines will be considered in some details.

2. Classification and general description of methods

The categories into which condition monitoring methods may be conveniently classified are the following:

(1) Visual monitoring
(2) Electric current monitoring
(3) Vibration monitoring
(4) Acoustic emission monitoring
(5) Wear debris monitoring
(6) Performance monitoring
(7) Thermal monitoring

2.1 Visual monitoring

This method ranges from a simple visual inspection by the unaided eye, through to the use of borescopes for better access, microscopes to increase magnification, and closed circuit television cameras. Results are normally obtained immediately, but they are not recorded automatically, and photography or videotape[e recording may be required if trends are to be established.

2.2 Electrical Current Monitoring

In electrical machines, some faults can be detected by measuring the currents or voltages in the machine windings. The magnetic field created near electrical machines changes when faults occur and therefore using induction loops to measure flux can also aid in condition monitoring.

2.3 Vibration monitoring

This is a very widely used technique which commonly employs a piezoelectric device to sense the acceleration of a moving part. A similar system using a microphone can also be used, but this may be more prone to interference.

The general principle behind vibration monitoring is that energy is supplied to the machine, and some of this is dissipated as vibrations. The spectral content of these vibrations will depend upon the energy input and the resonant frequencies of different parts of the machine. If the machines condition changes due to wear or damage, the resonant frequencies of the machine and hence the vibrations will change. The vibrations will however also change in the input energy changes.

Most vibration monitoring systems can be divided into three distinct parts: data acquisition, feature extraction and condition classification. Data is aquired using transducers. This is normally recorded in either analog or digital form on magnetic tape or computer disk. In simple systems it may however be possible to perform the analysis in real-time, removing the storage requirement and providing continuous monitoring. It is generally not possible to classify the condition based upon an individual sample of the vibration and therefore some transformation of the recorded vibration time-series is required to extract time-invariant features. In many cases the feature extracting transform used is also time-invariant and therefore the vibration signal has to be stationary.

In many cases, the power spectrum changes when faults occur. This is especially likely in rotating machinery where the vibrations are dominated by harmonics of the rotation frequency. Using the FFT can provide a fast estimate of the power spectrum although more accurate methods can be employed.

2.4 Monitoring Acoustic Emission

Acoustic emission is high frequency noise created when materials are structurally damaged. By monitoring this, the development of sudden cracks in the machine can be detected.

2.5 Oil Debris Analysis

Contact between different components in a machine causes wear such as when gear teeth mesh, minute amounts of metal are removed and end up in the lubricant. By analyzing the lubricant the rate of wear can be estimated and hence the condition of the machine.

2.6 Performance monitoring

Performance monitoring is a general term applied to on-line measurements of machine parameters and, as such, it also includes methods in other categories. Measurement of input and output power is a simple, but informative, form of performance monitoring

2.7 Thermal Monitoring

Machine faults such as an unbalanced shaft will increase the friction in the bearings and therefore the temperature will increase. Thermal imaging cameras can be used to detect such changes in temperature and therefore detect the fault.

3. Electrical machines failures

In the past, maintenance personnel relied upon a few basic tools and subjective methods of detecting pending failure. Did parts look, feel, smell or sound “different”? But today’s technology provides an arsenal of weapons and knowledge designed to determine a motor’s condition.

A well-maintained and monitored motor will be more reliable, thus eliminating costly downtime and unscheduled interruptions to production lines.

Motors fail in two different ways: mechanical failure due to improper installation, and improper or inadequate maintenance; and electrical failure due to overload and/or insulation deterioration that is detectable only through electrical and thermal monitoring. Understanding the various modes of failures is key to detecting specific motor faults [2] and scheduling maintenance efforts that prevent them. This article will provide some insights on predicting and preventing various kinds of motor failures that may lead to vibrations problems.

3. 1 Mechanical failures

A motor is an electro-mechanical device that converts electrical energy to mechanical energy. It is sometimes difficult to separate electrical faults from mechanical faults. However, the main mechanical conditions that can cause premature motor failures are: misalignment [3], unbalance, soft foot, bearing fatigue, overloading or overheating, inaccurate lubrication, and loss of cooling.

Bearing failures

Of all motor failures, approximately 40% are directly related to bearings. This is why reducing stress on bearings is essential in preventive maintenance[4]. Minimizing bearing stresses begins before the motor is installed. Since the weight of the rotor is supported by the bearings, handle the motor carefully to prevent alignments be performed, every application needs at least some alignment attention.

Soft foot

Soft foot occurs when all four motor feet do not rest smoothly on the mounting surface. The condition can be caused by an improperly machined motor base or by an uneven mounting surface. This condition should be corrected by the use of shims. To force all four feet flush to the mounting surface without shimming the soft foot can contort the motor frame and either stress the bearings or distort the motor air gap . A distorted air gap [5] can cause an impedance unbalance, which can result in a current unbalance, thus lead to excessive and uneven heating and/or shaft currents that cause premature bearing failure.

Lubrication problems

Too much lubrication can be as much of a problem as too little [6]. Greasing a bearing only helps if it’s done correctly. It’s actually better not to grease at all than to do it incorrectly. Most importantly, ensure grease fittings are wiped clean to prevent the introduction of dirt or grit into the bearing. It’s not required stopping a motor for regreasing, but that does minimize the possibility of grease leakage along the shaft seals and into the motor where it can accelerate the deterioration of the winding insulation.

Lubrication depends on the amount of usage (easy service, standard service, severe service, very severe service) of the motor in service.

If a motor is properly lubricated, mounted and handled, most common causes of bearing failure except fatigue are eliminated.. Vibration monitoring can detect bearing fatigue and most mechanical faults at a very early stage, along with some electrical faults.

Loss of cooling

Loss of cooling can mainly occur due to : obstructed air flow, fan damage, dust and debris on surface, cooling air short circuit, excessive altitude, and fouled heat exchangers. Many of these conditions can be detected by visual inspection but the symptom, excessive heat, which destroys motors is best detected using infrared thermography which is an effective tool for detecting hot spots in the motor core and in some cases, hot bearings in motors.

3.2. Electrical failures

The main conditions that can contribute to premature failure due to electrical problems [7] are: poor power quality, resistance unbalance, impedance unbalance, insulation failure, excessive loading/current, and overheating [8]. These are conditions that, if detected, can be corrected to extend the life of the motor and prevent any type of noise and vibration.

Poor power quality

Poor power quality can manifest itself in many forms [9]. With the increased use of variable speed drive and non-linear loads, harmonics are a common cause of poor power quality [10]. The use of properly sized line reactors can be an effective tool for isolating the harmonic condition and preventing its effects throughout the distribution system. Improper voltage level is another form of poor power quality. Additionally the motor may suffer from a voltage unbalance condition can cause current unbalances within the motor and thus, more noise and vibrations.

Winding resistance

Another condition leading to current unbalance and thus to vibrations is unbalanced winding resistance. This can be detected using a precision micro-ohm meter. resistance unbalances can be a result of high resistance connections in starters, or at the motor terminals. High resistance connections typically result in excessive heating at the connection point for which infrared thermography is an effective diagnostic tool.

Insulation resistance

The majority of motor electrical failures are due to breakdown of the winding insulation system. The winding condition can be evaluated by performing an insulation resistance measurement or sensing and analyzing with the motor on-line the voltage and vibration waveforms.

4. Vibration sources in rotating machines

Vibration and noise are natural processes in the machines and equipment and they are excited by the same dynamic forces that are the reasons of the wear and different types of defects.

Naturally, the vibration and noise transform from one into another on the border of gas and solid states, but the human being directly perceives only noise and only in limited low frequency range the vibration.

The oscillation velocity is responsible for the transformation of the vibration into noise. The inflationary pressure in air is proportional to the velocity of the oscillation surface. That is why the standards as, a rule, limit the oscillation velocity of the machines and equipment.

The sources of noise in electric machines may essentially be classified as mechanical and electrical [12]. Among the mechanical sources belong, for example, bearings (of which it is known that the rolling-contact types are more noisy than the sliding types) [13], ventilators (where the fundamental noise frequency is given by the product of the number of vanes and the speed in r.p.s), various siren effects (when, for instance, spacers in the rotor channels act as a siren), rebounding of brushes etc. Similar mechanical sources of noise apply also to non-electrical machines. They represent a fairly elaborated field and are beyond the scope of this paper.

This paper will reflect the most recent knowledge in the field of diagnosing anomalies in rotating machines, their problems and solutions using online condition monitoring to assure that the occurrence of unwanted higher vibrations will be minimized.

5. Dynamic forces in rotating machines

Dynamic forces act in each machine. These forces are the sources not only of the noise and vibration but the defects as well. These defects change the features of the forces and hence the characteristics of the noise and vibration. One can say that the machine functional diagnostics without changing the machine operation mode is the investigation of dynamic forces but not the vibration and noise. The latter only contain the information about the dynamic forces, but in the process of the transformation of dynamic forces into the vibration and noise some information is lost. Even more information is lost during transformation of the forces and their work into heat energy. That is why when there is a choice between two types of signal (temperature or vibration) in diagnostics vibration should be preferred.

The main dynamic forces that act in a rotating machine and excite its vibration and noise are the following:

Forces of *the mechanical* nature:

- Centrifugal forces

The main force applied to the rotor is the centrifugal force [14]. It has the frequency that equals the rotation frequency RPM/60 and a circular form. If there is any fault, especially a misalignment of rotors, the form will deviate from a circular one - in the spectrum appear superharmonics (multiple harmonics) kRPM/60.

- Parametric forces

The second force is the parametric one. It appears when the element has a splineway or such fault as a crack, viz. when the rigidity of the shaft depends on the rotation angle and changes twice per revolution. In this case in the vibration spectra even harmonics of the rotation frequency appear 2kRPM/60.

- The shock forces

The third force is the shock force [15]. It appears when the joint coupling has a defect. The joint coupling strips off from the stable position several times during the revolution and the shaft hits the bearings. As a result the jumps of the high frequency bearing vibration power appear several times per revolution (kRPM/60 in the envelope spectrum).

Forces of *the electrical and magnetic* nature:

- Magnetic forces

The electromagnetic forces [16] acting in the alternating current motors (induction motors and synchronous motors) have their own peculiarities - their frequency is twice the frequency of the magnetic field because it is proportional to the magnitude of the magnetic field ignoring its direction. So the main electromagnetic forces in an alternating current machine are acting with the frequency $2f_m$, where f_m is the frequency of the supply voltage (a.c. mains).

The second by its magnitude oscillating force has the slot frequency. The vibration with the slot frequency is sometimes called "magnetic noise". This vibration not always shows up visibly on the background of other components with nearby frequencies.

- Electrodynamic forces

When the rotor winding (squirrel cage) is absolutely symmetrical the electrodynamic forces have no alternating components. They generate only a constant (operating) torque. If the winding, i.e. the currents induced in it, is not symmetrical than a low frequency pulsating torque with a double slip frequency appears: $f_s = 2Sf_m$,

where S is the slip of the rotor that is equal $S=(f_m - pRPM/60)/f_m$. where p is the number of pole pairs.

If the field of the stator is unsymmetrical, i.e. besides the field that rotates in the main direction with the frequency f_m a badly compensated field, that rotates in the opposite direction, is present, then there appears an alternating electrodynamic force and correspondingly a torque of forces with a frequency $2f_m$. This situation appears both when there are unsymmetrical stator windings or when the power-line is unsymmetrical.

The electromagnetic field in the air gap of the direct current motor has much more complicated form than in the air gap of the alternating current motors with distributed winding of rotor and stator. The main poles form this field and when the motor is loaded a significant contribution give the additional poles. The main vibration component, i.e. the slot vibration harmonic, is defined by the fluctuations of certain parts of the air gap volume during the rotation of the slotted armature. However, If the motor is supplied by a rectifier then in the exciting circuit or in the armature circuit can appear besides the constant current also the alternating components of the current. In this case the electordynamic forces and vibration frequencies appear in the machine and they can be significantly large. Such vibration is especially seen when the motor is supplied by electronic rectifiers (Silicon Controlled Rectifierss).

6. Rotor balancing

Unbalance [17] is a common problem in industrial facilities. It is present in four out of every five machines and is most often detected in fans, motors, pumps and rolls. Unbalance is caused by:

- Broken welds or cracks
- Erosion, contamination, particle built-up
- Improper installation of equipment
- Wear

One of the most important applications of vibration analysis is the solution of balancing problems. An unbalanced propeller, rotor or drive shaft will cause

- Increased vibration
- Machinery breakdowns/premature failure
- Lost production
- Noise ergonomic issues
- Environmental concerns
- Undue stress on bearings, shafts, etc., and ultimate failure
- Wasted energy/ Increased energy cost

Balancing of a rotating part is therefore highly advisable in order to accomplish one or more of the following:

- Increase quality of ride.
- Minimize vibration.
- Minimize audible and signal noises.
- Minimize structural stresses.
- Minimize operator annoyance and fatigue.
- Increase bearing life.
- Minimize power loss.

<u>If unbalance is detected some procedures are needed:</u>

1. Record vibration data for each bearing location before taking corrective action.
2. Calculate the appropriate balance weights and locations and apply (or remove) Weights to eliminate unbalance.
3. Perform additional vibration analysis to confirm the machine is in balance.
4. Retain all data for reference should balancing be required in the future.

Defects in rotating machines can be identified via mainstream predictive technologies like vibration analysis, infrared thermography, ultrasound inspection, etc….

However, vibration analysis [18] is a logical first choice for most electrical machines. Because it is ideally suited for monitoring and analyzing the electrical and mechanical condition of rotating machines

<u>Rotational unbalance</u>

A rotating body will not exert any variable disturbing force on its supports when the axis of rotation coincides (concentric) with one of the principal axes of inertia of the body. This condition is quite difficult to achieve in the normal process of manufacturing since due to errors in geometrical dimensions and non-homogeneity of the material, some irregularities in the mass distribution are always present [19].

As a result of the above, variable disturbing forces occur which produce vibrations. To remove these vibrations and establish safe and quiet operation, balancing becomes necessary. The balancing becomes especially great in the case of high speed machines. In such cases the slightest unbalance may produce a very large disturbing force.

<u>Centrifugal force</u>

A rotating body having an uneven mass distribution or unbalance will vibrate due to the excess centrifugal force [14] exerted during rotation by the heavier side of the rotor. This unbalance causes centrifugal force, which in turn causes vibration. When at rest, the unbalance exerts no centrifugal force and does not cause vibration to occur. Yet, the actual unbalance is still present. Unbalance, therefore, is independent of rotational speed and remains the same, whether the rotor is at rest or is rotating (provided that the part does not deform during rotation). Centrifugal force, on the other hand, varies with speed. When rotation begins, the unbalance will exert centrifugal force tending to vibrate the rotor and its supporting structure. The higher the speed the greater the centrifugal force exerted by the unbalance and the more violent the vibration.

7. Mathematical model for the magnetic sources of noise

The forces acting between the stator and rotor, varying with time and space, may cause noise. According to Maxwell [20], at any point of the air gap acts a radial force whose magnitude per unit area may be expressed by the equation

$$p_r = B^2 (\alpha, t) / 2 \mu_o \quad (1)$$

Where B(α, t) is the instantaneous value of magnetic induction in the air gap at a point distant from a given axis by the periphery angle α at time t. After some work [21] we finally find the radial forces varying with time and having a diverse number of space waves may arise between the stator and the rotor as .

$$p_r = A_r \cos (r\, \alpha - \Omega_r\, t) \quad (2)$$

where r = 0,1,2,3,4… and Ω is the circular frequency of the force of the r th order.

The linear theory of the one-sided magnetic pull represents merely a more or less satisfactory approximation of reality because all the results (Fig.1) [22] of ump were calculated on open-circuit and neglecting the effect of saturation. The introduction of the latter would reduce the magnitude of the forces.

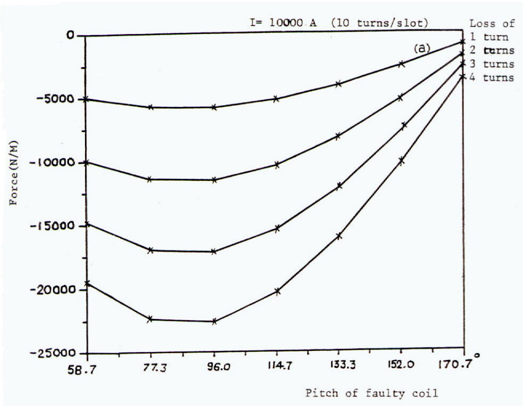

Fig.1 Force acting along the center of the faulty pole for two pole machine

Eccentricity is a major cause of the asymmetrical field in the air-gap. In fact, the source of unbalanced magnetic pull and the non-uniform rotor heating can itself cause eccentricity of dynamic type. As any form of eccentricity is likely to distort the output from sensors fixed in the air gap on the stator surface, we attempt to see the effect of such eccentricity and of the breakdown of a percentage of the rotor winding insulation Fig. 2 and 3 [5].

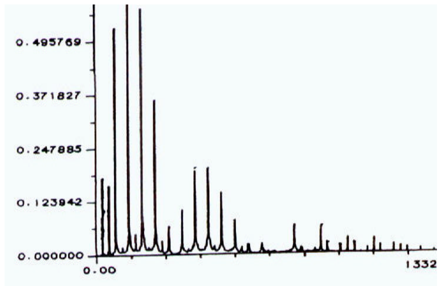

Fig.2 Frequency spectrum when 40% of the slot contents are omitted from coil of pitch 30°.

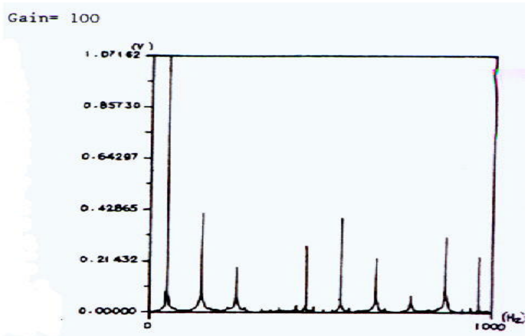

Fig.3Frequency spectrum with 20% eccentricity

Referring to all the experiment results, high load, eccentricity, or even the saturation cause the output to be distorted and makes the visual analysis or measurement very difficult. A helpful way to proceed is therefore to examine the harmonic spectrum or rotor winding short circuits, rotor eccentricity, and finally combined fault in the anticipation that each fault will have a unique spectrum. This will supply information about which harmonics to attempt to suppress by filtering and most important, which harmonics are common to different faults. The frequency spectrums did shoe clearly that the larger the eccentricity, the greater the magnitudes of odd multiples of 50 Hz.
Thus, it turns out that at least the important lower eccentricity harmonics are produced in approximate proportion to the of static eccentricity.

8. Conclusion

Monitoring anomalies using vibrations analysis is a powerful methods although sources of noise in rotating machines are very complicated phenomena and many factors such as stator and rotor slotting, air gap deformation, winding arrangement contribute to the existence of noise which is originally caused by vibrations of the machine parts. However some of the vibrations are easy to detect their origin by using different methods cited previously, but others are more complicated to localize and detect their origins. Vibration monitoring is very widely used technique, which commonly employs a piezoelectric device to sense the acceleration of a moving part. However in our research a technique based on sensors in the air gap of the machine was used and this latter will detect air gap signal which will be able to measure vibration in a principal direction, typically radial or axial, the frequency domain of the signal after examination and analysis does show its capability of indicating the type and location of the fault.

9. References

[1] Neale, M. , and Associated Ltd.: " A guide to the condition monitoring of machinery," (HMSO, 1979).

[2] Hennache, A., "On-line Control of Disturbances in Synchronous Machines." TENCON 98, International Conference on Global Connectivity in Energy, Computer, Communication and control. Dec., New Delhi, India.1998.

[3] Lees, A.W, "Towards machine models for fault diagnosis." Proceedings of the workshop on vibration in rotating machinery, april29- may 1, KFUPM, Dhahran, KSA.2000.

[4] Brown, P.J, "Preventive maintenance of machinery bearings." Maintenance Engineering, September, 1976.

[5] Hennache, A.S, Al-Nais, M.O, " Effect of rotor static eccentricity on the winding fault detection in synchronous machines." STCEX 2002, Oct., Riyadh, KSA,2002.

[6] Fuller, D.D, " Theory and practice of lubrication for engineers." John Wiley and Sons, Inc., New York,1963.

[7] Al-Nais M.O., Hennache, A.S., "Computerized diagnostic tools to monitor and assess the condition of a drive system." MEPCON '2001, DEC.29-31, Helwan university, Cairo, Egypt,2001.

[8] Rosenberg, L.T. , "Influence of shorted turns on thermal unbalance in large generators." IEEE_PES summer meeting, Los Angeles, CA, USA, July, Paper A78, pp. 587-588,1978.

[9] Math H.J.Bollen, "Understanding Power Quality Problems- Voltage Sags and Interruptions." The Fairmont Press, Prentice Hall,2000.

[10] IEEE Std. 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems". 1992.

[11] IEC 60505, "Evaluation and Qualification of Electrical Insulation",1999.

[12] McCloskey, T. H., Adams, M.L, " Troubleshooting power plant rotating machinery vibration using computational techniques: case histories." I. Mech.E. Conference on Vibrations in Rotating Machinery, Paper C432/137, 239-250, Bath, UK., 1992.

[13] Thomson, T., Sharp. D., " A bearing condition monitoring system in an Australian copper mine." IEE Conference on The Design, Application and Maintenance of Large industrial Drives," Publication No.170, November, pp. 45- 51. 1978.

[14] Ranking, W.A., " On the centrifugal force of rotating shafts," Phil. Trans. A, Vol. 185, p 279, 1969.

[15] Broch, J.T, " Mechanical vibration and shock measurements ", Bruel and Kjaer. 1980.

[16] Bratoljic, T., Vrkljam, P., " Magnetic forces created by rotor eccentricities in electrical machines." Brown Boveri Review, Vol.54, N0.9, Sept., pp.580=592.1967.

[17] Binns, K.J., Dye, M. , " Identification of principal factors causing unbalanced magnetic pull in cage induction motors.", Proceedings IEE, Vol.120, No.3, March, pp.349-354,1973.

[18] Al-Nais, M.O., Hennache, A.S., " Monitoring anomalies in large generators using flux and vibration spectra." Proceedings of the workshop on vibration in rotating machinery, april29- may 1, KFUPM, Dhahran, KSA.2000.

[19] Verma, S.P., Natarayan, R., "Effects of eccentricity in induction machine." Proceedings of the International Conference on Electrical Machines (ICEM), Budapest, Hungary, Sep.1982, pp.930-933.

[20] Hammond, P., " Applied electromagnetism." Pergamon Press, Oxford, p.191, 1971.

[21] Hennache, A.S., Al-Nais, M.O., " Parasitic phenomena occurring in rotating machines: Problems and Solutions.", Proceedings of STCEX 2002, pp.127-134, Riyadh 2002.

[22] Hennache, A.S., " Unbalanced magnetic pull in electrical machines." Proceedings of the First Saudi Technical Conference and Exhibition, Riyadh 18-22 November, pp.125-129, 2000.

[23] Bradford, M., " Unbalanced Magnetic Pull in a 6-pole Induction Motor." Proc. IEE, Vol.115, p.1619,1989.