

Fault Diagnostics of Electrical AC Machines

- **Literature Survey** -

Marian NEGREA

**Helsinki University of Technology
Laboratory of Electromechanics
P.O Box 3000, FIN-02015 HUT, Finland**

Phone number: + 358 40 733 4692

Fax number: + 358 9 451 2991

Email: marian.negrea@hut.fi

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1. Introduction

The operators of electrical drive systems are under continual pressure to reduce maintenance costs and prevent unscheduled down times, which result in lost production and financial income. Many operators now use on-condition based maintenance strategies in parallel with conventional planned maintenance schemes. This has reduced unexpected failures, increased the time between planned shutdowns for standard maintenance and reduced operational costs.

The operation of electrical machines in an unsafe condition can also be avoided. Since the incidence of unexpected failures is reduced the operator is able to exercise greater control in the prevention of incidents which may have environmentally damaging consequences. In hazardous installations, this requires continuous on-line monitoring to prevent a catastrophic failure.

During the past fifteen years there has been a substantial amount of research into the creation of new condition monitoring techniques for electrical machine drives. New methods have been developed which are now being used by the operators and research is continuing with the development of new and alternative on-line diagnostic techniques. However, it is still the operators who have to make the selection of the most appropriate and effective monitoring systems to suit their particular electric motor drive systems.

An operator must treat each motor drive as a unique entity and the potential failure modes, fundamental causes, mechanical load characteristics, and operational conditions have all to be taken into consideration when a monitoring system is being selected. Lately, the focus has been on the use of on-line condition monitoring to detect degradation processes and failure mechanisms of induction motors. Figure 1 presents an overview of problems and possible on-line monitoring techniques. In some cases there are several signals which may contain information on the failure mechanism. If possible, parameters, which will provide information on possible causes of failures, should also be monitored in addition to monitoring signals to identify fault mechanisms. These will ultimately lead to more intelligent drive systems, which are highly reliable, since the fundamental causes of premature failure can be substantially reduced.

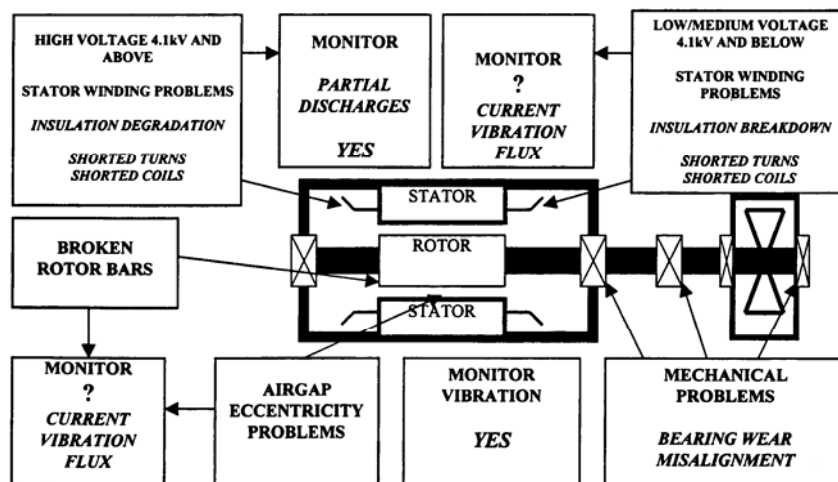


Figure 1. Problems, failures and possible on-line monitoring techniques for IM drives

2. Classification of the major faults of electrical machines and their symptoms

Most of the surveys of failures in electrical rotating machines indicate that in general, failures are dominated by bearing and stator winding failures with rotor winding problems being less frequent. The reported percentage failures by components for the sample was as follows [Benbouzid 2000]:

- bearing related 41 %
- stator related 37 %
- rotor related 10 %
- others 12%

The major faults of electrical machines can broadly be classified as the following:

- a) stator faults resulting in the opening or shorting of one 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 (dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings
- f) shorted rotor field winding, and
- g) bearing and gearbox failures.

These faults produce one or more of the symptoms as given below:

- a) Unbalanced air-gap voltages and line currents,
- b) Increased torque pulsations,
- c) decreased average torque,
- d) increased losses and reduction in efficiency, and
- e) excessive heating.

The diagnostic methods to identify the above faults may involve several different types of fields of science and technology. They can be described as:

- a) electromagnetic field monitoring, search coils, coils wound around motor shafts (axial flux related detection),
- b) temperature measurements,
- c) infrared recognition,
- d) radio frequency (RF) emissions monitoring,
- e) noise and vibration monitoring,
- f) chemical analysis,
- g) acoustic noise measurements,
- h) motor current signature analysis (MCSA),
- i) model, artificial intelligence and neural network based techniques.

Of the above types of faults 1) the stator or armature faults, ii) the broken bar and end ring faults of induction machines, iii) bearing, iv) the eccentricity related faults are the most prevalent ones and thus demand special attention in our research.

2.1 Various types of faults and their detection techniques.

A. Bearing faults

The majority of electrical machines use ball or rolling element bearings. Each of these bearings consists of two rings, one inner and the other outer. A set of balls or rolling elements placed in raceways rotate inside these rings. Even under normal operating conditions with balanced load and good alignment, fatigue failures may take place. These faults may lead to increased vibration and noise levels. Flaking or spalling of bearings might occur when fatigue causes small pieces to break loose from the bearing.

Other than the normal internal operating stresses, caused by vibration, inherent eccentricity, and bearing currents due to solid state drives, bearings can be spoiled by many other external causes such as:

- a) contamination and corrosion caused by pitting and sanding action of hard and abrasive minute particles or corrosive action of water, acid etc.
- b) improper lubrication; which includes both over and under lubrication causing heating and abrasion.
- c) Improper installation of bearing. By improperly forcing the bearing onto the shaft or in the housing (due to misalignment) indentations are formed in the raceways (brinelling).

Though almost 40-45% of all motor failures is bearing related, very little has been reported in literature regarding bearing related fault detection. Bearing faults might manifest themselves as rotor asymmetry faults, which are usually covered under the category of eccentricity related faults.

[Yazici 1997] have reported of an adaptive, statistical time frequency method for detection of bearing faults. Experiments were conducted on defective bearings with scratches on the outer races and bearing balls and cage defects. It has been claimed that all defective measurements were correctly classified as defective. However, the detection procedure required extensive training for feature extraction.

B. Stator or armature faults

These faults are usually related to insulation failure. In common parlance they are generally known as phase-to-ground or phase-to –phase faults. It is believed that these faults start as undetected turn-to-turn faults, which finally grow and culminate into major ones. Almost 30-40% of all reported induction motor failures falls in this category.

Armature or stator insulation can fail due to several reasons. Primaries among these are:

- a) high stator core or winding temperatures,
- b) slack core lamination, slot wedges and joints.
- c) Loose bracing for end winding.
- d) Contamination due to oil, moisture and dirt.

- e) Short circuit or starting stresses
- f) Electrical discharges
- g) Leakage in cooling systems

There are a number of techniques to detect these faults. [Penman 1997] was able to detect turn to turn faults by analysing the axial flux component of the machine using a large coil wound concentrically around the shaft of the machine. Even the fault position could be detected by mounting four coils symmetrically in the four quadrants of the motor at a radius of about half the distance from the shaft to the stator endwinding.

[Tolyiat 1995] has shown through both modelling and experimentation that these faults result in asymmetry in the machine impedance causing the machine to draw unbalance phase currents. This is the result of negative sequence currents flowing in the line as also have been shown in [Williamson 1984]. However, negative sequence currents can also be caused by voltage unbalance, machine saturation etc.

[Kliman 1996] model these unbalance which also includes instrument asymmetries. It is reported that with these modifications it is possible even to detect a one turn “bolted” fault out of a total 648 turns. Statistical process control (SPC) techniques have also been applied to detect stator faults [Dister 1994]

C. Broken rotor bar and end ring faults

Unlike stator design, cage rotor design and manufacturing has undergone little change over the years. As a result rotor failures now account for around 5-10% of total induction motor failures.

Cage rotors are of two types: cast and fabricated. Previously cast rotors were only used in small machines. However, with the advent of cast ducted rotors; casting technology can be used even for the rotors of machines in the range of 3000 kW. Fabricated rotors are generally found in larger or special application machines. Cast rotors though more rugged than the fabricated type, can almost never be repaired once faults like cracked or broken rotor bars develop in them.

The reasons for rotor bar and end ring breakage are several. They can be caused by:

- a) thermal stresses due to thermal overload and unbalance, hot spots or excessive losses, sparking (mainly fabricated rotors).
- b) Magnetic stresses caused by electromagnetic forces unbalanced magnetic pull, electromagnetic noise and vibration.
- c) Residual stresses due to manufacturing problems.
- d) Dynamic stresses arising from shaft torques, centrifugal forces and cyclic stresses.
- e) Environmental stresses caused by for example contamination and abrasion of rotor material due to chemicals or moisture.
- f) Mechanical stresses due to loose laminations, fatigued parts, bearing failure etc.

[Kliman 1988], [Thomson 1988], [Filippetti 1996], [Elkasabgy 1992] used spectrum analysis of machine line current (MCSA) to detect broken bar faults. They investigate the sideband components around the fundamental for detecting broken bar faults.

[Elkasabgy 1992] has also shown that broken bar faults can also be detected by time and frequency domain analysis of induced voltages in search coils placed internally around stator tooth tip and yoke and externally on motor frame.

Following the work of [Penman 1986], detection of these faults is also possible by frequency domain analysis of shaft flux or more generally axial leakage flux which is monitored by using an external search coil wound around the shaft of a machine. Modelling of rotor bar and end ring faults have been described by [Tolyat 1995]. Broken bar detection using state and parameter estimation techniques have also been reported [Cho 1992]. However, the current spectrum and the parameter estimation approach have been compared and the former has been found more efficient [Filipetti 1994].

D. Eccentricity related faults

Machine eccentricity is the condition of unequal air-gap that exists between the stator and rotor [Vas 1993], [Cameron 1986]. When eccentricity becomes large, the resulting unbalanced radial forces (also known as unbalanced magnetic pull or 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. 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 centre of the rotor is not at the centre 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. Dynamic eccentricity in a new machine is controlled by the total indicated reading (TIR) or “run-out” of the rotor [Thomson 1997]. An air-gap eccentricity of up to 10 % is permissible. However, manufacturers normally keep the total eccentricity level even lower to minimise UMP and to reduce vibration and noise.

The presence of static and dynamic eccentricity can be detected using motor current signature analysis - MCSA [Vas 1993], [Cameron 1986]. Modelling based approaches to detect eccentricity related components in line current have been described in [Nandi 1998-1], [Nandi 1998-2]. 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 [Cameron 1986].

Time stepping finite element methods have been employed recently to compare simulated results with experimentally obtained static eccentricity components in line currents [Barbour 1997]. Static eccentricity has also been modelled using Winding Function Approach [Toliyat 1996].

Other approaches, such as monitoring the stator voltage and Current Park's Vector [Cardoso 1993] to detect eccentricity in induction motor, can also be found in literature. [Tolyiat 1997] has provided simulation and experimental results for synchronous machines with dynamic eccentricity related faults.

3. Electrical machines signature analysis as a medium for faults detection

This section is intended as a tutorial overview of electric motors (mostly induction motors) signature analysis as a medium for fault detection. The purpose is to introduce in a concise manner the fundamental theory, main results, and practical applications of motor signature analysis for the detection and the localisation of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of induction motors. Many of the papers surveyed inhere are focused on the so-called motor current signature analysis which utilises the results of spectral analysis of the stator current.

Induction motors are a critical component of many industrial processes and are frequently integrated in commercially available equipment and industrial processes. Motor-driven equipment often provides core capabilities essential to business success and to safety of equipment and personnel. There are many published techniques and many commercially available tools to monitor induction motors to insure a high degree of reliability optime. In spite of these tools, many companies are still faced with unexpected system failures and reduced motor lifetime. Environmental, duty, and installation issues may combine to accelerate motor failure far sooner than the designed motor lifetimes. Critical induction motor applications are found in all industries and include all motor power ratings. It has been found that many of the commercial products to monitor induction motors are not cost effective when deployed on typical low- to medium-horse-power induction motors. Advances in sensors, algorithms, and architectures should provide the necessary technologies for effective incipient failure detection [Siyambalapatiya 1990], [Discenzo 1997].

In this context, a variety of sensors could be used to collect measurements from an induction motor for the purpose of failure monitoring. These sensors might measure stator voltages and currents, air-gap and external magnetic flux densities, rotor position and speed, output torque, internal and external temperature, case vibrations, etc. In addition, a failure monitoring system could monitor a variety of motor failures. These failures might include conductor shorts and opens, bearing failures, cooling failures, etc. It is apparent then, that a failure monitoring system should be capable of extracting, in a consistent manner, the evidence of many possible failures from measurements from many physically different sensors [Bonnett 1992], [Vas 1993], [Kliman 1992], [Benbouzid 1997].

In general, condition-monitoring schemes have concentrated on sensing specific failure modes in one of three induction motor components: the stator, the rotor, or the bearings. Even though thermal and vibration monitoring have been utilised for decades, most of the recent research has been directed toward electrical monitoring of the motor with emphasis on inspecting the stator current of the motor. In particular, a large amount of research has been directed toward using the stator current spectrum to sense rotor faults associated with broken rotor bars and mechanical unbalance.

All of the presently available techniques require the user to have some degree of expertise in order to distinguish a normal operating condition from a potential failure mode. This is because the monitored spectral components (either vibration or current) can result from a number of sources, including those related to normal operating conditions. This requirement is even more acute when analysing the current spectrum of an induction motor since a multitude of harmonics exist due to both the design and construction of the motor and the variation in the load torque. However, variations in the load torque, which are not related to the health of the motor typically, have exactly the same effect on the load current. Therefore, systems to eliminate induction motors arbitrary load effects in current-based monitoring have been proposed [Schoen 1995], [Schoen 1997].

Condition monitoring of the dynamic performance of electrical drives received considerable attention in recent years. Many condition monitoring methods have been proposed for different type of rotating machine faults detection and localisation. In fact, large electromachine systems are often equipped with mechanical sensors, primarily vibration sensors based on proximity probes. Those, however, are delicate and expensive. Moreover, in many situations, vibration-monitoring methods are utilised to detect the presence of incipient failure.

However, it has been suggested that stator current monitoring can provide the same indications without requiring access to the motor. This technique utilises results of spectral analysis of the stator current (precisely, the supply current) of an induction motor to spot an existing or incipient failure of the motor or the drive system [IAS 1985], [IAS 1987], [Thorsen 1995], [Finlay 1994], [Belmans 1985].

3.1. Fault effect on stator current spectrum

A. Air-Gap Eccentricity

Two main types of methods have been proposed for the detection of an air-gap eccentricity. The first ones monitor the behaviour of the current at the sidebands of the slot frequencies [Cameron 1986]. The second methods monitor the behaviour of the current at the fundamental sidebands of the supply frequency [Kliman 1992].

B. Broken Rotor Bars

Broken rotor bars are detected by monitoring the motor current spectral components produced by the magnetic field anomaly of the broken bars. A complete paper dealing with this analysis is [Kliman 1992].

C. Bearings Damage

Installation problems are often caused by improperly forcing the bearing onto the shaft or in the housing. This produces physical damage in the form of brinelling or false brinelling of the raceways which leads to premature failure. Misalignment of the bearing, is also a common results of defective bearing installation. The relationship of the bearing vibration to the stator current spectra can be determined by remembering that any air-gap eccentricity produces anomalies in the air-gap flux density. Since ball

bearings support the rotor, any bearing defect will produce a radial motion between the rotor and stator of the machine.

D. Load Effects

If the load torque does vary with rotor position, the current will contain spectral components, which coincide with those caused by a fault condition. When the induction machine operates with a typical time-varying load, the torque oscillation results in stator currents that can obscure, and often overwhelm, those produced by the fault condition. Therefore, any stator current single-phase spectrum based fault detection scheme must rely on monitoring those spectral components, which are not affected by the load torque oscillations. However, broken bars detection is still possible since the current typically contains higher order harmonics than those induced by the load [Kliman 1990].

3.2 Fault detection techniques

Modern measurement techniques in combination with advanced computerised data processing and acquisition show new ways in the field of induction machines monitoring by the use of spectral analysis of operational process parameters (e.g., temperature, pressure, steam flow, etc.). Time-domain analysis using characteristic values to determine changes by trend setting, spectrum analysis to determine trends of frequencies, amplitude and phase relations, as well as cepstrum analysis to detect periodical components of spectra are used as evaluation tools (Fig. 2). In many situations, vibration-monitoring methods were utilised for incipient fault detection. However, stator current monitoring was found to provide the same indication without requiring access to the motor [Kliman 1992], [Kliman 1990].

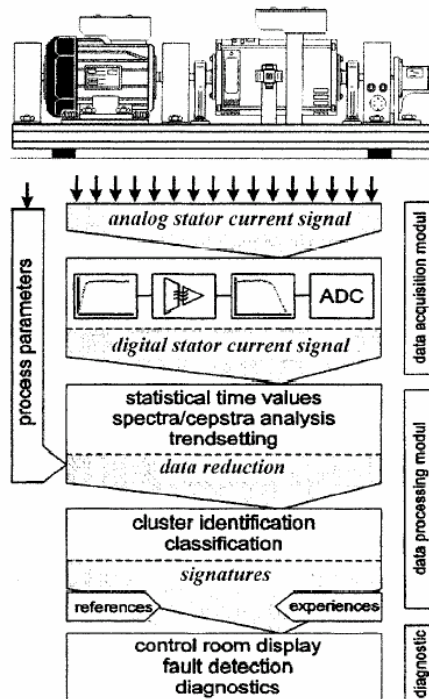


Fig. 2 A basic stator current monitoring system configuration [Benbouzid 2000]

In what follows some of the main stator-current- signature-based techniques are presented:

A. Classical Fast Fourier Transform (FFT)

For this method, the stator current monitoring system contains the four following processing sections shown in Fig. 3.

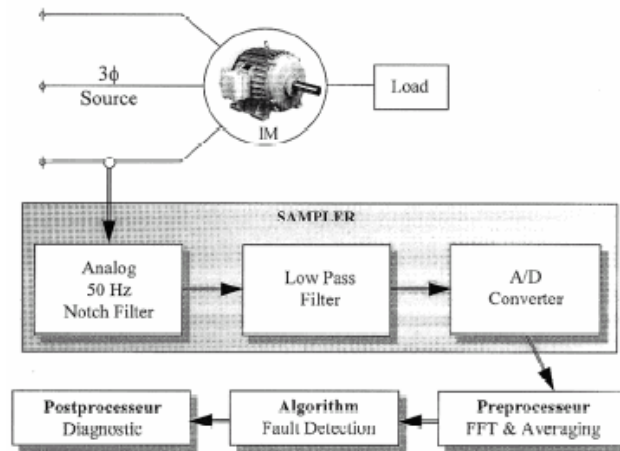


Fig. 3 One phase stator current monitoring system [Benbouzid 2000]

1) *Sampler*: Its purpose is to monitor a single-phase stator current. This is accomplished by removing the 50-Hz excitation component through low-pass filtering, and sampling the resulting signal. The single-phase current is sensed by a current transformer and sent to a 50-Hz notch filter where the fundamental component is reduced. The analogue signal is then amplified and low-pass filtered. The filtering removes the undesirable high-frequency components that produce aliasing of the sampled signal while the amplification maximises the use of the analog-to-digital (A/D) converter input range. The A/D converter samples the filtered current signal at a predetermined sampling rate that is an integer multiple of 50 Hz. This is continued over a sampling period that is sufficient to achieve the required FFT.

2) *Pre-processor*: It converts the sampled signal to the frequency domain using an FFT algorithm. The generated spectrum includes only the magnitude information about each frequency component.

Signal noise that is present in the calculated spectrum is reduced by averaging a predetermined number of generated spectra. This can be accomplished by using either spectra calculated from multiple sample sets or spectra computed from multiple predetermined sections (or windows) of a single large sample set. Because of the frequency range of interest and the desired frequency resolution, several thousand frequency components are generated by the processing section.

3) *Fault Detection Algorithm*: In order to reduce the large amount of spectral information to a usable level, an algorithm, in fact a frequency filter, eliminates those components that provide no useful failure information. The algorithm keeps only those components that are of particular interest because they specify characteristic frequencies in the current spectrum that are known to be coupled to particular motor faults. Since the slip is not constant during normal operation, some of these components are bands in the spectrum where the width is determined by the maximum variation in the motor slip.

4) *Postprocessor*: Since a fault is not a spurious event but continues to degrade the motor, the postprocessor diagnoses the frequency components and then classifies them (for each specified fault).

Conclusion: *Generally, not denying the diagnostic value of classical spectral analysis techniques, induction motor faults detection, via FFT-based stator current signature analysis, could be improved by decreasing the current waveform distortions of the spectrum noisiness [Benbouzid 1997], [Benbouzid 1998].*

B. Instantaneous Power FFT

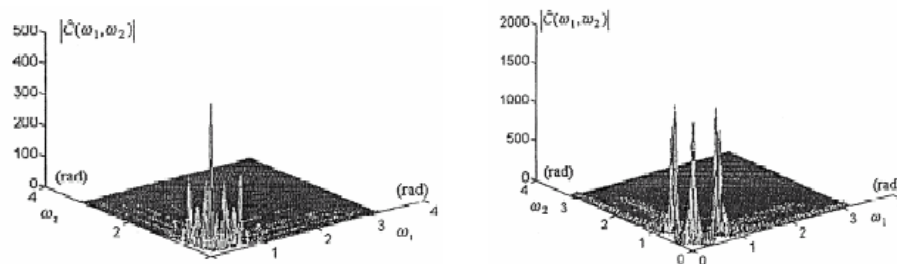
In this case, in place of the stator current, the instantaneous power is used as a medium for the motor signature analysis oriented toward mechanical faults detection in a drive system [Legowski 1996], [Trzynadlowski 1997]. It was shown that the amount of information carried by the instantaneous power, which is the product of the supply voltage and the motor current, is higher than that deducible from the current alone. In fact, besides the fundamental and the two classical sideband components, the instantaneous power spectrum contains an additional component directly at the modulation frequency.

All the fault harmonics are translated into the frequency band 0–100 Hz. This constitutes a great advantage because the fault harmonics domain is well bounded. *However, the power spectra are still noisy, so as instantaneous power FFT, at this stage, does not bring important improvement. Therefore, the stator current should be maintained as the main medium for the motor signature analysis.*

C. Bispectrum

Bispectrum, also called third-order spectrum, emerges from higher order statistics. The bispectrum is defined in term of the two-dimensional Fourier transform of the third-order moment sequence of a process [Arthur 1998], [Chow 1995], [Chow 1996].

Very promising results were obtained, as illustrated by Fig. 4. In fact, experimental results indicate that the bispectrum magnitude of the dominant component, caused by the machine rotation, increased with the fault level increase. *These results clearly indicate that stator current bispectrum is capable of providing adequate and essential spectral information for induction motors condition monitoring and faults detection. This technique should be particularly applied to detect electrical- based faults, such as stator voltage unbalance, because those faults do not have an well-identified harmonic frequency component [Benbouzid 1999].*



reference condition (healthy machine)

stator winding faults condition

Fig. 4 Bispectrum [Chow 1995].

D. High-Resolution Spectral Analysis

The classical spectral estimation techniques, which have been used, are among the most robust ones, allowing computationally efficient algorithms like the FFT. However, a main disadvantage of the classical spectral estimation is the impact of side lobe leakage due to the inherent windowing of finite data sets.

In order to improve the statistical stability of the spectral estimate, i.e., to minimise the estimate variance, pseudo ensemble averaging by segmenting the data was introduced at the price of further decreasing the resolution. Therefore, trade-offs among stability, resolution, and leakage suppression are necessary. A class of spectral techniques based on an eigenanalysis of the autocorrelation matrix has been promoted in the digital signal processing research literature. They may improve or maintain high resolution without sacrificing as much stability, allowing us to keep only the principal spectral components of the signal and to decrease noise influence.

E. Wavelet Analysis

The Fourier analysis is very useful for many applications where the signals are stationary. The Fourier transform is, however, not appropriate to analyse a signal that has a transitory characteristic such as drifts, abrupt changes, and frequency trends. To overcome this problem, it has been adapted to analyse small sections of the signal at a time. This technique is known as short-time Fourier transform (STFT), or windowing technique. The adaptation maps a signal into a two-dimensional function of time and frequency. The STFT represents a sort of compromise between time- and frequency-based views of a signal and it provides some information about both. However, we can only obtain this information with limited precision, and that precision is determined by the size of the window. The fixed size of the window is the main drawback of the STFT [Da Silva 1997]. The wavelet transform was then introduced with the idea of overcoming the difficulties mentioned above. A windowing technique with variable-size region is then used to perform the signal analysis, which can be the stator current. Wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information. The ability to perform local analysis is one of the most interesting features of the wavelet transform [Galli 1996].

The advantages of using wavelet techniques for fault monitoring and diagnosis of induction motors are increasing because these techniques allow us to perform stator current signal analysis during transients. The wavelet technique can be used for a localised analysis in the time-frequency or time-scale domain. It is then a powerful tool for condition monitoring and fault diagnosis. These results show the improvements introduced by the wavelet technique for the signal frequency monitoring [Wang 1996].

F. Techniques to be Associated to Motor Current Signature Analysis (MCSA)

In what follows, techniques, which can be associated to the MCSA, will be briefly presented.

F1. Park's Vector Approach:

A two-dimensional representation can be used for describing three-phase induction motor phenomena, a suitable one being based on the stator current Park's vector [Cardoso 1993]. This representation is a circular pattern centred at the origin of the coordinates. This is a very simple reference figure that allows the detection of faulty conditions by monitoring the deviations of the acquired patterns as illustrated by Fig. 5. The healthy pattern differs slightly from the expected circular one, because supply voltage is generally not exactly sinusoidal. The results obtained by the extended Park's vector approach are more discriminative than those obtained by the traditional FFT-based MCSA recommended [Kim 1997].

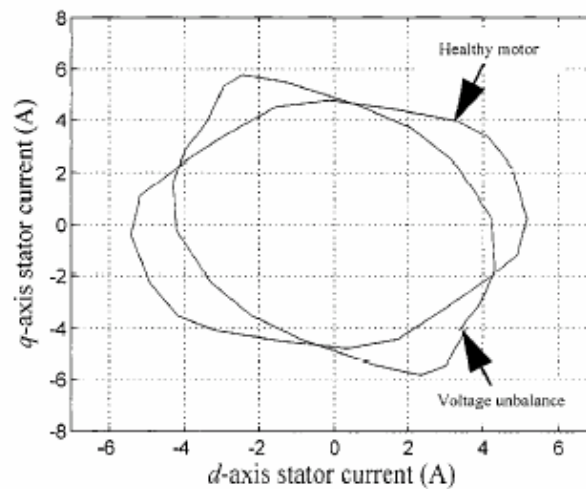


Fig. 5 Stator Current Park's Vector Approach

F2. Finite-Element Method

The above-cited works were mainly developed from an experimental standpoint. However, accurate analysis of an induction motor under faulted conditions (particularly transient) is very difficult. Some works have then reported on the introduction of numerical methods to aid in understanding fault manifestation.

Once known, faults are accurately simulated, the technique can be used to predict how other, more difficult to identify, faults can be detected via MCSA [Watson 1997], [Fiser 1997], [Kim 1997]. The finite-element method, which is well established, for induction motors modelling, could be used to provide an accurate evaluation of the magnetic field distribution inside the motor. Perturbation in this field distribution would indicate fault presence, e.g., a broken rotor bar. Less common rotor faults, such as broken end rings and faults in double-cage designs could be investigated using a finite-element model. To assess the magnetic saturation effect on fault detection, the time-stepping finite-element method is recommended [Kim 1997].

Literature on the electrical machines signature analysis as a medium for fault detection

This section presents more detailed descriptions of the most representative papers dealing with the signature analysis as a medium for faults detection for electrical machines.

[Benbouzid 2000]: El Hachemi Benbouzid, M., "A review of induction motors signature analysis as a medium for faults detection", Industrial Electronics, IEEE Transactions on, Volume: 47 Issue: 5, Oct. 2000, Page(s): 984 –993.

This paper is intended as a tutorial overview of induction motors signature analysis as a medium for fault detection. The purpose is to introduce in a concise manner the fundamental theory, main results, and practical applications of motor signature analysis for the detection and the localisation of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of induction motors. The paper is focused on the so-called motor current signature analysis, which utilises the results of spectral analysis of the stator current. The paper is purposefully written without "state-of-the-art" terminology for the benefit of practising engineers in facilities today who may not be familiar with signal processing.

[Callies 1999]: H. Calis, P.J. Unsworth, "Fault diagnosis in induction motors by motor current signal analysis", The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 237-241, 1999, Gijon, Spain.

This paper presents a short review of fault prediction in three phase induction motors. The common mechanical problems of the shaft misalignment, bearing faults, and load unbalance are treated experimentally using motor current and vibration signal analysis techniques. Algorithms, based on spectral estimation, are described and tested, which identify faults from amplitude changes of characteristic frequency components generated in the motor signals. The background noise level in the spectrum is also used as a fault indicator.

[Yazici 1999]: Yazici, B.; Kliman, G.B., "An adaptive statistical time-frequency method for detection of broken bars and bearing faults in motors using stator current", Industry Applications, IEEE Transactions on, Volume: 35 Issue: 2, March-April 1999, Page(s): 442 –452.

In this paper, the authors present an adaptive, statistical, time-frequency method for the detection of broken bars and bearing faults. Due to the time-varying normal operating conditions of the motor and the effect of motor geometry on the current, they employ a training-based approach in which the algorithm is trained to recognise the normal operating modes of the motor before the actual testing starts. During the training stage, features which are relevant to fault detection are estimated using the torque and mechanical speed estimation. These features are then statistically analysed and segmented into normal operating modes of the motor. For each model, a representative

and a threshold are computed and stored in a database to be used as a baseline during the testing stage. In the testing stage, the distance of the test features to the mode representatives are computed and compared with the thresholds. If it is larger than all the thresholds, the measurement is tagged as a potential fault signal. In the postprocessing stage, the testing is repeated for multiple measurements to improve the accuracy of the detection. The experimental results from their study suggest that the proposed method provide a powerful and a general approach to the motor-current-based fault detection.

It was shown that the time–frequency spectrum reveals the properties relevant to fault detection better than the Fourier spectrum in the transform domain. The method is based on a training approach in which all the distinct normal operating modes of the motor are learned before the actual testing starts. This study suggests that segmenting the data into homogenous normal operating modes is necessary, because different operating modes exhibit different statistical properties due to non-stationary nature of the motor current. Overlooking this fact will deteriorate the performance of the detection. It was shown that signals from faulty motors are several hundred standard deviations away from the normal operating modes, which indicates the power of the proposed statistical approach.

Also, new methods of estimating fault frequencies based on torque and mechanical speed estimations are presented. It was shown that a window of frequency components around the estimated fault frequencies has to be monitored, because the estimates, even in the case of exact knowledge of the motor geometry and the operating conditions, are never accurate. This approach also allows to efficiently process frequency components, which are spread due to low-frequency resolution.

Summarising, the study suggests that the proposed method is a mathematically general and powerful one, which can be utilised to detect any fault that could show up in the motor current.

[Joksimovic 2000]: Joksimovic, G.M.; Penman, J., “The detection of inter-turn short circuits in the stator windings of operating motors”, Industrial Electronics, IEEE Transactions on, Volume: 47 Issue: 5, Oct. 2000, Page(s): 1078 –1084.

This paper develops a winding-function-based method for modelling polyphase cage induction motors with inter-turn short circuit in the machine stator winding. Analytical consideration, which sheds light on some components of the stator current spectra of both healthy and faulty machines, is developed. It is shown that, as a result of the nature of the cage rotor, no new frequency components of the line current spectra can appear as a consequence of the fault. Only a rise in some of the frequency components, which already exist in the line current spectra of a healthy machine, can be observed. An experimental set-up comprising a 3 kW delta-connected motor loaded by a generator was used to validate this approach. The experimental results obtained clearly validate the analytical and simulation results.

The results from both the simulation and experimental analysis show that frequency component at 150 Hz increases under the action of the inter-turn short-circuit condition. It is well known that this frequency component already exists in the line current spectra of a healthy machine as a result of saturation of magnetic material. Also, this

component is sensitive to other asymmetries from the stator side, such as unbalanced voltage supply.

Further, it has been demonstrated that, under the short-circuit condition, a significant rise in rotor slot harmonics components $(1 \pm \lambda n (1-s)/p) f$ occurs; these components exist in a healthy machine. These frequency components are also sensitive to some other abnormal machine conditions, such as unbalanced voltage supplies or static eccentricity conditions. Clearly, these components cannot be used as a specific sign of the occurrence of inter-turn short circuits in stator windings.

[Filippetti 1994]: Filippetti, F.; Franceschini, G.; Tassoni, C.; Vas, P., "Broken bar detection in induction machines: comparison between current spectrum approach and parameter estimation approach", Industry Applications Society Annual Meeting, 1994., Conference Record of the 1994 IEEE, 1994, Page(s): 95 -102 vol.1.

In this paper the diagnosis of induction machine rotor electrical faults is considered. Two approaches are compared: the current spectrum analysis and the apparent rotor resistance estimation. For the first approach the authors have developed several procedures based on different fault models of the machine. Their experience is used to approach the parameter estimation method from a theoretical point of view: the resistance variation of the balanced per-phase model is computed using the faulted machine model. It is possible to obtain, by the simulation, the expected resistance variation when some bars break in a specific machine. Moreover the numerical results can be generalised. Using a simplified model of a faulted machine a relationship is obtained, which correlates the apparent resistance variation with the number of broken bars. This relationship needs several assumptions and therefore it is an approximate one, but can be used to define the threshold level for the apparent resistance variation expected in the case of one broken bar. By this relationship it is possible to have an indication on the sensitivity of the parameter estimation approach. The superiority of the current spectrum approach over the parameter estimation approach is shown.

Three methods based on the spectrum computation of instantaneous current values to determine the anomalous line corresponding to rotor asymmetries, which has been thoroughly investigated by the authors allow not only to detect rotor failure but also to diagnose "healthy rotors", with the application of artificial intelligence techniques. The equivalent models of faulty machines, which form the basis of this procedure, have been applied to determine the theoretical deviation of the rms current value in the per-phase equivalent circuit of the symmetrical machine in case of a rotor failure. An approximate value for the case of one broken bar has also been derived, this can be used as a reference value to develop interesting considerations on the precision that can be reached through the two diagnostic approaches.

It can be concluded that the spectrum analysis approach has the features required by an efficient diagnostic system for broken bar detection, while the parameter estimation approach gives unambiguous results only in the case of more than a few broken bars.

[Watson 1999]: Watson, J.F., "The use of line current as a condition-monitoring tool for three-phase induction motors", Design, Operation and Maintenance of High

Voltage (3.3 kV to 11 kV) Electric Motors for Process Plant (Ref. No. 1999/178), IEE Colloquium on, 1999, Page(s): 6/1 -6/4

Many researchers have worked on the problem of detecting rotor faults in induction machines while the machine is still in operation. The methods proposed have been varied, including the measurement of rotor speed [Hargis 82] to look for the fault indicating speed ripple, the measurement of vibration at the machine stator housing [Cameron 86] and the measurement of axial fluxes [Penman 78]. The main problem concerning these monitoring methods is that they are essentially invasive, requiring transducers to be fitted in or around the machine with the obvious interruption to operation.

For the above reasons, line current has become the favoured parameter for the purpose of detecting rotor faults in squirrel cage induction motors [Williamson 82, Rankin 89, Schoen 94]. Line current can be monitored noninvasively via clip-on current transducers hence no interruption to the machine operation is required, and the system can be made versatile and portable. Recent work has seen the development of the technique to monitoring the current of the motor while under transient conditions during start-up [Elder 92]. As discussed below this can, under certain conditions, offer distinct advantages over steady state monitoring.

This paper has reported on the continuing development of the use of line current as a parameter on which to base on-line condition monitoring techniques applicable to 3-phase induction motors.

The development of transient monitoring techniques has extended the operating range of such systems to permit the monitoring of machines in operational conditions, which would not be appropriate to more conventional analyses. The work has also shown that modern signal processing techniques can, and will, form the basis of the development of the next generation of condition monitoring tools.

[Pillay 1996]: Pillay, P.; Xu, Z., "Motor current signature analysis", Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS '96., Conference Record of the 1996 IEEE, Volume: 1, 1996, Page(s): 587 -594 vol.1.

This paper shows how the speed of an induction motor (IM) can be extracted from the motor currents of an induction motor with a Labview implementation of motor current signature analysis. The implementation is first applied to an IM driven by the 60 Hz mains. The estimation system consists of data acquisition, demodulation, and FFT spectrum analyses. The estimation is then extended to PWM inverter-fed IM drives. For PWM drives, the presence of stator current harmonics and a variable fundamental frequency demands filtering and a more powerful demodulation technique. The above estimation algorithms are implemented in Labview for Windows.

[Bellini 2000]: Bellini, A.; Filippetti, F.; Franceschini, G.; Tassoni, C.; Kliman, G.B., "Quantitative evaluation of induction motor broken bars by means of electrical signature analysis", Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, Volume: 1, 2000 Page(s): 484 -491 vol.1.

The paper reports the comparison and performance evaluation of different diagnostic procedures that use input electric signals to detect and quantify rotor breakage in induction machines supplied by the mains. Besides the traditional current signature analysis based on one-phase current spectrum lines at frequencies $(1\pm 2s) f$, the procedures based on analysis of the line at frequency $2sf$ in the spectrum respectively of electromagnetic torque, space vector current modulus and instantaneous power are considered. These last procedures have similar features and the comparison is developed on the basis of instantaneous torque. It is shown that the speed ripple introduces two further terms in the instantaneous torque, decreasing the accuracy of the diagnosis. It is shown that there is a link between the angular displacement of the current sideband components at frequencies $(1\pm 2s) f$. This allows a more correct quantitative evaluation of the fault and to show the superiority of the sideband current components diagnostic procedure over the other proposed methods.

In order to diagnose the condition of rotor bars, several methods have been proposed, which rely on the computation of suitable electric variables, starting from current and voltage signals. In the paper, together with the most commonly adopted current signature analysis, based on FFT analysis of one phase stator current, other diagnostic procedures based on FFT analysis of current space vector modulus, instantaneous power and torque have been deeply discussed.

In summary it has been proven that current signature analysis provides the information to diagnose accurately and quantitatively the rotor breakage. Specifically an effective diagnostic index can be retrieved summing the amplitudes of the two sidebands components in the current spectrum. Alternative diagnostic methods, which use current space, vector modulus, as well as instantaneous power, or instantaneous torque loss information and thus do not allow an accurate qualification of the breakage, since they are affected twice by the speed reaction. For the specific fault considered, the information inside one-phase current and space vectors requires more computational effort, therefore this procedure can be adopted for a more complete diagnostic systems, dedicated to other faults detection.

[Bellini 2001]: A. Bellini, F. Filipetti, G. Franceschini, C. Tassoni, T.J. Sobczyk, " Unique classification of single frequency induction motors features introduced by different anomalies", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 435-440.

The presence of anomalies in induction machines can be detected from the FFT analysis of the current space vector. Specifically if only one specific line introduced by the anomaly is considered, the amplitude of the spectrum line at frequency $(1-2s) f$ is the most investigated signal for rotor anomalies detection, while for stator anomalies the line at frequency $- f$ can be utilised. However since different anomalies may produce the same effect, the discrimination of different anomalies, without requiring other signal features, is an open challenge.

In this paper a methodology is presented, which allows separating the different anomalies, monitoring the variations of the specific spectral components amplitude with the slip.

An approach for the diagnosis of different anomalies in induction machines using only the specific spectrum line introduced by stator or rotor asymmetry is used in this work. The different faults are discriminated by means of the analysis of the different shapes of amplitude variations versus slip. The specific spectrum lines are the $-f$ component for the stator anomalies and the $(1-2s)f$ component for the rotor ones. The correlation between their amplitude and the slip has been found through the so-called mono-harmonic models of the faulty machine that allows the computation of these components as negative sequence components. Simplified assumptions are then applied for the machine operating near the rated slip value.

Referring the line amplitude to the fundamental component, as usual in FFT algorithms application, we can summarised the results as follow:

- rotor electric anomalies as bar breakage or an additional resistance produce a quite constant variation of the $(1-2s)f$ line amplitude with the slip.
- Rotor magnetic anomalies as magnetic asymmetry produce variation of the $(1-2s)f$ line amplitude proportional to $1/s$.
- Stator electric anomalies as additional resistance produce a constant variation of the $-f$ line amplitude with the slip.
- Stator electric anomalies as short circuits produce a variation of the $-f$ line amplitude proportional to $1/s$
- Stator magnetic anomalies as magnetic asymmetry produce a variation of the $-f$ line amplitude proportional to $1/s$
- Voltage negative sequence produces a variation of the $-f$ line amplitude proportional to $1/s$, but this contribution can be easily removed.

There are only two anomalies, stator short-circuit and stator magnetic asymmetry, that need further diagnostic features in order to separate their effects.

[Bellini 2001-2]A. Bellini, G. Franceschini, N. Petrolini, C. Tassoni, F. Filipetti, "On-line diagnosis of induction drives rotor by signal injection techniques: faults location and severity classification", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 531-536.

New components that are introduced in the induction machines current spectrum by added signals injected by the inverter can be used for both sensorless control and for diagnostics. Specifically for control purposes rotor intrinsic asymmetries effect is used to track the angular information, while for diagnostic purposes the tracking of the new current components can be used to detect rotor faults. When the event occurs, a rotor asymmetry is present. Activating a diagnostic procedure is possible to state the fault severity as well.

The paper shows how the most common procedures for sensorless control of electric drives can be used for diagnostic aims. Specifically a periodically burst injection in

input voltages is made and sensorless procedures are implemented to estimate angular information by tracking the additional current component introduced by broken bars. Therefore if the estimated angular position is in agreement with the actual position a rotor fault has occurred. Then an alert signal is activated and the off-line procedure for the fault severity classification is employed. Specifically the FFT analysis of input currents is made and the amplitude of the additional component is analysed.

If the off-line procedure confirms the occurrence of a rotor fault, the location of the broken rotor bar is detected manually checking when the current reaches its minimum. This allows to retrieve the broken bar position, provided that an absolute reference is available, with the ambiguity of pair poles number. This is an efficient aid for the retrieval of broken bar position, which can be very helpful for the maintenance of large machines. Other techniques for the fault location in the literature require spectrogram analysis of currents and a more complex procedure.

[Fiser 1995]: Fiser, R.; Ferkolj, S.; Solinc, H., "Steady state analysis of induction motor with broken rotor bars", Electrical Machines and Drives, 1995. Seventh International Conference on, 1995, Page(s): 42 –46.

The paper presents a mathematical model of a squirrel cage induction motor, taking account of higher space harmonics, and a computer simulation of induction motor fault states. The authors have studied the case of broken rotor bars as the source of rotor electrical asymmetry. Based on the mathematical model, the computer simulation of the influence of rotor cage defects on torque and current characteristics of induction machines at different slip values is presented. The practical monitoring of cage asymmetry is discussed by using spectral analysis of the line current of an induction machine. The laboratory tests of both healthy motor and motors with broken rotor bars show good agreement with these simulation results.

As it was specified above, the paper discusses method for the steady-state analysis of symmetrically supplied three-phase induction machine. The equations have been established in natural and in rotor reference frame. The presented method of calculation of rotor bar currents allows us to determine current flow distribution for any slip value. The calculation of stator and rotor currents, motor torque as well as magnetic field distribution in the cross-section of the motor represents a practical tool for monitoring the possible effects or emergency states which can be obtained from harmonic analysis of frequency spectrum of stator current.

The most obvious indication of rotor cage asymmetry is the increased level and number of higher harmonics in the stator current spectrum, which lead to increased level of electromagnetic noise and vibrations especially during starting. The simulation and experimental results show that on-line spectrum analysis of the current can be used to detect broken bars.

[Thomson 1995]: Thomson, W.T., "On-line current monitoring to detect rotor winding and electromechanical problems in induction motor drives", Condition Monitoring of Electrical Machines, IEE Colloquium on, 1995, Page(s): 8/1 -8/6.

To prevent the unexpected failure of large three-phase induction motors, it is necessary to detect fault mechanisms at an early stage when the motor is still in service. This requires the use of reliable, online, diagnostic monitoring systems to detect the problems and thus enable a repair to be carried out at a convenient time to avoid disruption to production requirements. The repair can also be planned when the manpower and component parts are available. An online condition based maintenance strategy can thus avoid costly failures and potentially hazardous conditions. This paper concentrates on the application of current monitoring to detect rotor winding and electromechanical problems in induction motor drives. Reference is also included on the analysis of the current signal to indicate purely mechanical problems in the drive system.

[Thomson 2001]: Thomson, W.T.; Fenger, M., "Current signature analysis to detect induction motor faults", IEEE Industry Applications Magazine, Volume: 7 Issue: 4, July-Aug. 2001, Page(s): 26 –34.

This article focuses on the industrial application of motor current signature analysis (MCSA) to diagnose faults in three-phase induction motor drives. MCSA is a non-invasive, online monitoring technique for the diagnosis of problems in induction motors.

The industrial case histories have clearly demonstrated that MCSA is a powerful technique for monitoring the health of three-phase induction motors. An essential ingredient of the diagnostic strategy is the inclusion of mechanical load/drive train characteristics, operational load condition at the time of diagnosis, motor design, duty cycle and rating of the motor, etc. Existing MCSA systems tend to use a combination of a front-end signal conditioner, a spectrum analyser, and a PC.

[Zhang 2001]: Zhang, X.H.; Cao, Y.N.; Li, Y.L., "A new project for motor fault detection and protection", Developments in Power System Protection, 2001, Seventh International Conference on (IEE), 2001, Page(s): 145 –148.

This paper discusses a project that is used for detection and protection of the electrical and mechanical faults of motors. Through extracting the characteristics of sequence currents under all kinds of the electrical faults, the authors proposed a simple and comprehensive protective scheme in protection units. At the same time, by analysing the spectrum of the stator currents with wavelet transforms, one can detect the mechanical faults of motors, such as broken rotor bars, etc.

The project of motor protection and detection, proposed in this paper, provides comprehensive protection for motor that is based on the features of sequence currents, at the same time; it can monitor and detect mechanical faults of the motor at a remote distance based on the frequency analysis of stator currents by wavelet transform.

[Zhongming 2000]: Zhongming Ye; Bin Wu, "Induction motor mechanical fault simulation and stator current signature analysis", Power System Technology, 2000.

Proceedings. PowerCon 2000. International Conference on, Volume: 2, 2000, Page(s): 789 -794 vol.2.

This paper addresses the simulation of induction machines with mechanical faults and the fault signature analysis of stator current. Models for three-phase induction motors with broken rotor bars by winding function method are developed. Current waveforms of an induction motor under normal and faulty conditions are simulated. New feature coefficients for signature analysis of the stator current are proposed based on the wavelet packet decomposition. The feature coefficients are calculated for both normal and fault conditions. It is shown that for most load conditions the new feature coefficients for fault cases are distinctive from normal conditions at certain depth and nodes. The features proposed here can be used for induction motor fault detection and diagnosis.

[Franceschini 1993]: Franceschini, G.; Tassoni, C., "Time harmonic investigation of flux density in the stator and rotor frame oriented to diagnostics of cage induction machines", Electrical Machines and Drives, 1993. Sixth International Conference on, 1993, Page(s): 103 –108.

Condition monitoring of electric machines is increasing in importance: the continuous assessment of the machine performance allows scheduling appropriately maintenance, so increasing machine operating life and reducing repair cost. The monitoring system must give an early indication of the onset of possible malfunctions. Therefore a great amount of study is in progress to associate an unambiguous symptom to the corresponding malfunction, so to obtain a univocal correspondence cause-effect. Among the different diagnostic techniques, the spectral components present in the machine variables allow the identification of several fault conditions. Here, the authors describe how the current spectrum and the flux density spectrum are widely considered in the diagnostic systems applied to induction machines.

[Benbouzid 1999]: Benbouzid, M.E.H.; Nejjari, H.; Beguenane, R.; Vieira, M., "Induction motor asymmetrical faults detection using advanced signal processing techniques", Energy Conversion, IEEE Transaction on, Volume: 14 Issue: 2, June 1999, Page(s): 147 –152.

Preventive maintenance of electric drive systems with induction motors involves monitoring of their operation for detection of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of the system. Intensive research effort has been for sometime focused on the motor current signature analysis. This technique utilises the results of spectral analysis of the stator current. Reliable interpretation of the spectra is difficult, since distortions of the current waveform, caused by the abnormalities in the drive system are usually minute. In the present investigation, the frequency signature of some symmetrical rotor faults are well identified using the Fast Fourier Transform (FFT), leading to a better interpretation of the motor current spectra. Laboratory experiments indicate that the motor current signature FFT-based analysis, with the proposed approach, is still a reliable tool for induction motor symmetrical faults detection.

It has been demonstrated that the stator current high-resolution spectral analysis, proposed as a medium for induction motors faults detection, has definite advantages over the traditionally used FFT spectral analysis.

Extensive experimental studies are necessary to fully assess usefulness of the proposed technique for the preventive maintenance diagnostics and failure prevention in drive systems with induction motors.

[Benbouzid 1999]: Benbouzid, M.E.H.; Vieira, M.; Theys, C., "Induction motors faults detection and localisation using stator current advanced signal processing techniques", Power Electronics, IEEE Transactions on, Volume: 14 Issue: 1, Jan. 1999, Page(s): 14 –22.

This paper addresses the application of motor current spectral analysis for the detection and localisation of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of induction motors. Intensive research effort has been for some time focused on the motor current signature analysis. This technique utilises the results of spectral analysis of the stator current. Reliable interpretation of the spectra is difficult since distortions of the current waveform caused by the abnormalities in the induction motor are usually minute. This paper takes the initial step to investigate the efficiency of current monitoring for diagnostic purposes. The effects of stator current spectrum are described and the related frequencies determined. In the present investigation, the frequency signature of some asymmetrical motor faults is well identified using advanced signal processing techniques, such as high-resolution spectral analysis. This technique leads to a better interpretation of the motor current spectra. In fact, experimental results clearly illustrate that stator current high-resolution spectral analysis is very sensitive to induction motor faults modifying main spectral components, such as voltage unbalance and single-phasing effects.

This paper has taken the initial step to investigate the efficiency of current monitoring for diagnostic purposes. The effects of stator current spectrum have been described and the related frequencies determined. In the present investigation, the frequency signatures of some asymmetrical motor faults have been well identified using advanced signal processing techniques, such as high-resolution spectral analysis. Experimental results have demonstrated that the stator current high-resolution spectral analysis, proposed as a medium for induction motors faults detection, has definite advantages over the traditionally used FFT spectral analysis, and, more generally, this technique will be useful in all faults modifying main spectral components.

[Burnett 1995]: Burnett, R.; Watson, J. F.; Elder, S., "The application of modern signal processing techniques to rotor fault detection and location within three-phase induction motors", Instrumentation and Measurement Technology Conference, 1995. IMTC/95. Proceedings. Integrating Intelligent Instrumentation and Control., IEEE, On page(s): 426, 24-26 April 1995.

Faults within the rotors of large three phase induction motors, such as broken bars, can be detected by monitoring and analysing the line current taken by the machine during a no-load starting transient [Watson 92], [Elder 90].

The line current has been shown to contain frequency components, which are indicative of these fault conditions. Under transient conditions these components are however non-stationary in both the time and frequency domains. Signal processing strategies applicable to time variant data such as The Spectrogram, The Wigner Ville Distribution and Wavelet Decomposition have been implemented and their success in detecting these non-stationary components evaluated. The most suitable of these techniques has been used to determine the occurrence and severity of motor faults. Preliminary work suggests that these techniques may also be used to detect frequency components indicative to the location of the fault.

It has been shown that by using a signal processing technique which obtains the Time-Frequency representation of multi-component non-stationary signals, it is possible to detect the presence of the non-stationary components within the transient line current of a 3 phase induction motor supply which are indicative of rotor faults, such as broken rotor bars. The amplitude of these non-stationary components is proportional to the severity of the fault. This processing technique has been simplified and installed on a portable PC along with a specifically developed acquisition system. This forms the basis of a portable motor monitoring system, which enables the operator to determine the health of the motor, by monitoring the supply current transient under no load conditions.

[Legowski 1996]: Legowski, S.F.; Sadrul Ula, A.H.M.; Trzynadlowski, A.M., "Instantaneous power as a medium for the signature analysis of induction motors", Industry Applications, IEEE Transactions on, Volume: 32 Issue: 4, July-Aug. 1996. Page(s): 904 –909.

Preventive maintenance of electric drive systems with induction motors involves monitoring of their operation for detection of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of the system. Intensive research effort has been for sometime focused on the motor current signature analysis (MCSA). The MCSA techniques utilise the results of spectral analysis of the stator current. Reliable interpretation of the spectra is difficult, since distortions of the current waveform caused by the abnormalities in the drive system are usually minute. In this paper, an alternate medium for the motor signature analysis, namely the instantaneous power, is proposed. By theoretical analysis, computer simulations, and laboratory experiments, it is shown that the instantaneous power carries more information than the current itself. Utilisation of the instantaneous power is thus enhancing the reliability of diagnostics of induction motor drives.

[Trzynadlowski 2000]: Trzynadlowski, A.M.; Ritchie, E., Comparative investigation of diagnostic media for induction motors: a case of rotor cage faults, Industrial Electronics, IEEE Transactions on , Volume: 47 Issue: 5 , Oct. 2000, Page(s): 1092 – 1099.

Results of a comparative experimental investigation of various media for noninvasive diagnosis of rotor faults in induction motors are presented. Stator voltages and currents in an induction motor were measured, recorded, and employed for computation of the partial and total input powers and of the estimated torque. Waveforms of the current,

partial powers, total power, and estimated torque were subsequently analysed using the Fast Fourier Transform. Several rotor cage faults of increasing severity were studied with various load levels. The partial input power was observed to exhibit the highest sensitivity to rotor faults. This medium is also the most reliable, as it includes a multiplicity of fault-induced spectral components.

Extensive experiments carried out on an induction motor with various rotor faults and under various load conditions have shown the usefulness of the total and partial instantaneous power as diagnostic media for rotor faults in induction machines. The stator current, which is regularly used in motor signature analysis, yielded inferior results.

The study was limited to rotor faults only. Therefore, any extension of the ranking of the individual diagnostic media would be inappropriate. It is conceivable that the fault sensitivity of each medium depends on the type of fault present, and more research is certainly needed.

[Cruz 1999]: Cruz, S.M.A.; Cardoso, A.J.M., "Rotor cage fault diagnosis in three-phase induction motors by the total instantaneous power spectral analysis", Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE , Volume: 3 , 1999. Page(s): 1929 -1934 vol.3.

This paper deals with the use of the total instantaneous power spectral analysis for diagnosing the occurrence of rotor cage faults in operating three-phase induction motors. The theoretical principles directly related to the application of this diagnostic technique are described, emphasising the role of parameters such as the magnetising current, motor-load inertia, motor rating and load level, in the diagnostic process. Both simulation and laboratory tests results to demonstrate the effectiveness of the total instantaneous power spectral analysis for diagnosing the presence of rotor cage faults. The development of a severity factor, in order to evaluate the extension of the fault, is reported, and it is shown how this severity factor is almost independent of parameters such as the magnetising current, motor rating and motor-load inertia.

The experimental and simulation results show that rotor cage faults can be effectively detected by the identification of a characteristic component at a frequency of $2sf$, in the total instantaneous power spectrum.

It is demonstrated that the amplitude of this characteristic component is directly related to the amplitude of the two motor current spectral components, at frequencies of $(1\pm 2s)$ f. Due to the relationship between these motor current spectral components and the motor-load inertia, the characteristic component of the total instantaneous power already incorporates the effect of this parameter in the diagnostic process.

A normalised severity factor, defined as the ratio of the amplitude of the $2sf$ component and the dc level of the total instantaneous power, prove to be a good indicator about the extension of the fault, since it takes into account the influence of parameters such as the magnetising current, motor rating, or the motor-load inertia.

[Drif 2001]: M. Drif, N. Benouzza, B. Kraloua, A. Bendiabdellah, J.A Dente "Detection of voltage source dissymetry using the measurement of the symmetrical components in working induction motors", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 461-467.

This paper deals with the application of the spectral analysis of the instantaneous power for the detection of rotor cage faults in operating three phase induction motors. This approach carries more information than that of the current spectral analysis approach. Both simulation and experimental results are presented to illustrate the merits of the proposed instantaneous approach.

The paper introduces a new approach, based on a spectral analysis of the instantaneous power for detecting the occurrence of rotor cage faults in operating three-phase induction motors. The experimental and simulated results show that rotor cage faults can be effectively detected by this new technique, whose operating approach relies on the behaviour of the spectral component at frequency of $2sf$. This characteristic spectral component of power appears directly at the frequency of disturbance, independently of the synchronous speed of the motor. This is important in automated diagnostic system, in which the irrelevant frequency component i.e., those multiples of the supply frequency, is screened out.

It is known that broken bar faults generate side-band components at frequencies differing from the fundamental by only the double slip frequency. Clearly it would be difficult to filter out the fundamental without affecting the side-band component. In contrast, the characteristic component in the spectrum of the power can easily be separated from the dc component by compensation of the latter one. The spectrum of the power provides easier filtering conditions, than that of the stator current.

Furthermore, the use of this variable for the detection of bar faults allows us to have simultaneous information on the current and voltage. For example, in the case of unbalance of the supply voltage, which is not taken into account in the conventional method of the current spectrum. So this technique allows us to monitor the motor by two different electrical variables: voltage and current.

[Arthur 2000]: Arthur, N.; Penman, J., "Induction machine condition monitoring with higher order spectra", Industrial Electronics, IEEE Transactions on, Volume: 47 Issue: 5, Oct. 2000, Page(s): 1031 –1041.

This paper describes a novel method of detecting and unambiguously diagnosing the type and magnitude of three induction machine fault conditions from the single sensor measurement of the radial electromagnetic machine vibration. The detection mechanism is based on the hypothesis that the induction machine can be considered as a simple system, and that the action of the fault conditions are to alter the output of the system in a characteristic and predictable fashion. Further, the change in output and fault condition can be correlated allowing explicit fault identification. Using this technique, there is no requirement for a priori data describing machine fault conditions, the method is equally applicable to both sinusoidally and inverter-fed induction machines and is generally invariant of both the induction machine load and speed. The detection

mechanisms are rigorously examined theoretically and experimentally, and it is shown that a robust and reliable induction machine condition-monitoring system has been produced. Further, this technique is developed into a software-based automated commercially applicable system.

This paper has presented the predictive frequency method of induction machine condition monitoring. It has shown that using simple system, induction machine, and high order spectra (HOS) theory it is possible to construct a general and robust method of determining the health of induction machines. A thorough experimental analysis has been conducted which has verified the theoretical approach, and demonstrated the versatility of these techniques. Further, the automation of these methods into a generalised condition-monitoring tool of commercial viability has been presented, this tool precluding the requirement for user intervention or interpretation. Although this paper reports only on single machine failures, the occurrence of multiple failures simultaneously is also detectable using these techniques and is the subject of further work in this area.

[Nandi 2000]: Nandi, S.; Toliyat, H.A., "Novel frequency domain based technique to detect incipient stator inter-turn faults in induction machines", Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, Volume: 1, 2000, Page(s): 367 -374 vol.1

Traditionally, for medium and high voltage motors and generators, condition based monitoring (CBM) of stator faults are performed by measuring partial discharge (PD) activities. For low voltage machines, negative sequence impedance or currents are measured for the same. Such prognosis schemes should be carefully implemented as supply voltage unbalance, manufacturing related asymmetry, etc. also produce negative sequence voltages. A few motor current signature analysis (MCSA) based approaches have already been proposed to detect stator inter-turn faults. However little or no physical insight was provided to explain the occurrence of certain harmonics in the line current or the influence of voltage unbalance on these harmonics. Also, in at least one of the papers, a large portion of the stator winding was shorted to emulate the faults. The method proposed in these paper monitors certain rotor slot related harmonics at the terminal voltage of the machine once it is switched off. In the absence of supply voltage, issues such as voltage unbalance and time harmonics do not influence the measurements except as initial conditions; a very desirable feature when the machine is fed from an adjustable speed drive. Satisfactory simulation and experimental results have been obtained with only about 1.5% (5/324) of the total number of turns shorted.

A novel stator inter-turn fault detection scheme by the presence of certain harmonics at the terminal voltages of an induction machine immediately after switch-off was discussed. The physics behind the production of such harmonics are explained in detail. Unlike negative sequence current or impedance measurements, this technique is insensitive to supply voltage unbalance. The very nature of the test also suggests that the supply harmonics have little influence on detectability. Corroborative simulation and experimental results have been presented.

[Cabanas 1999]: M. F Cabanas, M.G Melero, G.A. Orcajo, J.M Cano, F. Briz del Blanco, G.A Capolino, "A new methodology for applying the FFT to induction motor on-line diagnosis", The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 537-544, 1999, Gijon, Spain.

The Discrete Fourier Transform, DFT, is a mathematical transformation, which allows the calculation of the frequency components of periodical non-sinusoidal signals. The DFT is usually applied to electrical machines for the detection of incipient rotor or mechanical failures. In these cases, the transform is used to decompose real variable functions, which vary in time, such as the machine phase current or vibration into its frequency components. However, this mathematical tool can be easily applied to complex sequences such as Park's vector of currents or voltages. In these cases, the resulting frequency spectrum can be seen as decomposition into complex rotating vectors. This paper presents the theoretical basis for the application of the DFT to complex functions, as well as possibility of improving some aspects of induction motor diagnosis by means of this new processing technique.

A new procedure to apply the fast Fourier Transform to complex variable functions and a generalisation of the DFT for the case of complex sequence have both been described. It has been shown that this new technique allows the rotating sequence for all the frequency components included in the processed signal to be determined. The application of this technique to on-line inter turn short circuit detection in random-wound induction motors has also been presented. A new procedure for the calculation of the inverse sequence impedance has been proposed, and the experimental results have shown a much higher simplicity and stability in the measurement than procedures described in previous studies.

[Assaf 2001]: T. Assaf, H. Henao, G.A Capolino, "Detection of voltage source dissymetry using the measurement of the symmetrical components in working induction motors", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 441-447.

The present paper describes a new procedure for the on-line computation of the symmetrical components in working induction motors. Such parameters have been introduced as good indicators of the voltage source dissymetry in power systems. An experimental test-bed with a 0.12 kW star-connected induction motor has been used to test the procedure. The algorithm used to compute the symmetrical components is based on the discrete Fourier transform (DFT) with a number of samples particularly adapted to the sampling frequency. The stability of the numerical results will be shown to prove the performance of the proposed algorithm.

On-line monitoring of symmetrical component as the inverse voltage and the inverse current can provide a simple and effective method for detecting voltage power supply unbalance. Moreover, the use of this method is simple and the interpretation of the results does not require specific knowledge. A new technique for computing the module and the argument of the inverse sequence impedance has been proposed. This technique can be implemented in a simple hardware with three voltage and three current sensors.

The experimental results show the validity and the accuracy of method, which can be extended for higher harmonic impedances.

[Cardoso 1999]: Marques Cardoso, A.J.; Cruz, S.M.A.; Fonseca, D.S.B., “Inter-turn stator winding fault diagnosis in three-phase induction motors, by Park's Vector Approach”, Energy Conversion, IEEE Transaction on. On page(s): 595 – 598 Sept. 1999.

The subject of on-line detection and location of inter-turn short circuits in the stator windings of three-phase induction motors is discussed, and a non-invasive approach, based on the computer-aided monitoring of the stator current Park's Vector, is introduced. Experimental results, obtained by using a special fault producing test rig, demonstrate the effectiveness of the proposed technique, for detecting inter-turn stator winding faults in operating three-phase induction machines.

The on-line diagnosis is based on identifying the appearance of an elliptic pattern, corresponding to the motor current Park's Vector representation, whose ellipticity increases with the severity of the fault and whose major axis orientation is associated to the faulty phase.

[Nejjari 2000]: Nejjari, H.; Benbouzid, M.E.H., ”Monitoring and diagnosis of induction motors electrical faults using a current Park's vector pattern learning approach”, Industry Applications, IEEE Transactions on, Volume: 36 Issue: 3, May-June 2000, Page(s): 730 –735.

Various applications of artificial neural networks (ANN's) presented in the literature prove that such technique is well suited to cope with online faults diagnosis in induction motors. The aim of this paper is to present a methodology by which induction motors electrical faults can be diagnosed. The proposed methodology is based on the so-called Park's vector approach. In fact, stator current Park's vector patterns are first learned, using ANN's, and then used to discern between “healthy” and “faulty” induction motors. The diagnosis process was tested on both classical and decentralised approaches. The purpose of a decentralised architecture is to facilitate a satisfactory distributed implementation of new types of faults to the initial NN monitoring system. The generality of the proposed methodology has been experimentally tested on a 4-kW squirrel-cage induction motor. The obtained results provide a satisfactory level of accuracy, indicating a promising industrial application of the hybrid Park's vector–neural networks approach.

Experimental tests have led to results with a level of accuracy greater than 97%, which is satisfactory and promising for an industrial application of the hybrid Park's vector–NN's approach.

[Cardoso 1999]: A.J Marques Cardoso, A.M.S Mendes, S.M.A Cruz, “The Park's vector approach: new developments in on-line fault diagnosis of electrical machines power electronics and adjustable speed drives”, The 1999 IEEE International

Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 89-98, 1999, Gijon, Spain.

A global perspective of the new developments of the Park's vector approach, for on-line fault diagnostics of electrical machines, power electronics and adjustable speed drive is presented in the paper. Full details of the theory, experimental results, on-site case histories, and current developments are presented, concerning the on-line fault diagnosis of three-phase power transformers, induction machines and variable speed AC drives.

The global perspective of the new developments of the Park's vector approach, presented in this paper, reinforced the previous conclusion [Cardoso 1997], that this is truly a powerful general tool for diagnostics of electrical machines, power electronics and adjustable speed drives.

[Cruz 2001]: S.M.A Cruz, A.J Marques Cardoso, " Further Developments on the use of the synchronous reference frame current Park's Vector Approach", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 467-472.

This paper is intended to exploit the use of the synchronous reference frame current Park's Vector Approach in the diagnosis of rotor cage faults in operating three-phase induction motors, when in the presence of time-varying loads. It is shown how this Park's Vector Approach can be used to detect and quantify the extension of the fault when the motor is running smoothly. The issues related with the consequences of the presence of time-varying loads are also stressed, emphasising its implications in the quantification of the extension of fault. The subject of the motor performance degradation, when the motor has developed a rotor asymmetry is also addressed, and it is shown how the Park's Vector Approach can be used to predict this performance degradation.

It was shown that when the motor is coupled to a constant load, the rotor asymmetry can be diagnosed by the identification of an elliptic figure, in the current Park's Vector Approach pattern, whose major radius is directly related with the extension of the fault. A severity factor can be defined in order to quantify the extension of the fault, in a way quite independent of the motor parameters.

The presence of a time-varying load manifests itself in the current Park's Vector Approach pattern mainly by the perturbation of the q-axis component of the current Park's Vector while the d-axis component only suffers slight variations. This result is important as it allows to distinguish the presence of a time-varying load from the truly existence of a rotor asymmetry.

[Perovic 2000]: Kostic-Perovic, D.; Arkan, M.; Unsworth, P., "Induction motor fault detection by space vector angular fluctuation", Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, Volume: 1, 2000, Page(s): 388 -394 vol.1.

A new method of obtaining diagnostic data from induction motors, derived from space vector angular fluctuation, is presented in this paper. It obtains data from stator current by exploring the position of the current space vector in the space vector plane. Variations of the phase angle of the vector are subjected to Fourier transformation and analysed in the frequency domain. The method has been tested on laboratory induction motors with simulated stator faults, rotor resistance unbalance, supply voltage unbalance, as well as with computer simulation. The Goertzel algorithm is employed as a tool for real-time fault monitoring of the frequency domain. In the case of a stator fault, which can develop rapidly, this allows diagnosis within a few cycles. As well as providing a new tool in motor diagnostics, this method is able to detect both stator and rotor faults, and gives a good basis for an integrated induction motor condition monitor.

Angular fluctuations of the induction motors current space vector are used as a new source of diagnostic data for stator and rotor induction motor faults. The SVAF (space vector angular fluctuation) method is defined as a method that monitors indicative changes in the diagnostic data, through analysing characteristic frequencies in the spectrum of the space vector angular fluctuations. Some diagnostic indices for stator and rotor fault are listed.

[Fiser 2001]: R. Fiser, D. Makuc, V. Ambrozic, "Evaluation of the induction motor cage fault stage using finite element method", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 627-631.

This paper presents the application of a finite element method for predicting the performance of induction motor having electric and magnetic asymmetry of rotor cage due to some broken rotor bars. Magnetic field was calculated for the case of symmetrical rotor cage and for several cases of rotor electrical asymmetry. Quantities like magnetic vector potential, flux density force components, rotor and stator currents, and mutual and leakage inductance were determined very precisely taking into account the magnetic materials non-linearity.

The detailed insight in magnetic field distribution of a squirrel cage induction motor forms the basis for further evaluation of its operational behaviour. Increasing anomaly in magnetic field distribution due to the increasing number of broken rotor bars in a degradation of steady-state and dynamic performance of induction motor and can be determined with computer simulation eliminating expensive and time consuming laboratory tests. The obtained results are compared with measurements. Correct evaluation of faulty motor performance is very significant part of condition monitoring and diagnostic procedure in modern supervision systems of electrical drives.

Computer simulation based on mathematical models presents effective and inexpensive method for studying the influence of different motor faults on drive performance. The finite element method was used to calculate magnetic field of induction motor with symmetrical (healthy) and asymmetrical (faulty) rotor cage. The presented method allows to determine induced currents in rotor cage and calculate steady-state and transient characteristics of induction motor for the case of any number and position of broken rotor bars. The method has proved a significant applicability in the process of fault diagnosis of induction motors.

[Thomson 1999]: Thomson, W.T.; Barbour, A., “The on-line prediction of airgap eccentricity levels in large (MW range) 3-phase induction motors”, Electric Machines and Drives, 1999. International Conference IEMD ‘99, 1999, Page(s): 383 –385

The focus of this paper is to apply time stepping finite element analysis to model large (MW), 11 kV, 3-phase induction motors as a function of the combination of static and dynamic airgap eccentricity. An industrial case history is presented to confirm the validity of the theoretical predictions and actual diagnosis.

The time stepping FE predictions have confirmed previously observed phenomena [Cameron 87], [Cameron 86], [Thomson 97]. The FE analysis has to be done off-line due to the computing power required but the predictor curves can be subsequently included into an on-line current monitoring system such that the degree of severity of airgap eccentricity can now be estimated. This has not been previously reported for large induction motors. Predictor curves can also be produced for a range of load conditions hence the diagnosis from on-line current analysis can cater for load variations.

[Rojas 2001]: C.H Rojas, M.G. Melero, M.F Cabanas, M.P Donsion, M. Eteve, V. Vina Olay, A. Arguelles Amado, ” Analysis by the finite element method of the influence caused in the current distribution in rotor squirrel-cage IM and current spectrum by the number and distribution of faulty bars during a rotor failure”, The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 479-486.

Studies of rotor asymmetries in squirrel cage induction motors have focused on analyses of the effects on the magnetic field and current spectrum of breakage of contiguous bars. However, ABB Company has reported several cases where damaged bars are randomly distributed around the rotor perimeter of large HV machines. Moreover, a recent study carried out by our research group showed that breakage of a single bar leads to asymmetrical current distribution in the rotor that displays certain transient increases in areas of the cage that are considerably distant from the failure point. These abnormal currents may be the origin of progressive damage at different points of the cage. For these two reasons a study was carried out to investigate the influence that the number and position (contiguous or random) of faulty bars has on the rotor current distribution and current spectrum of asynchronous motor.

The results presented allow the following conclusions to be reached:

- rotor bar breakage produces secondary effects in the rotor current layer. The distortion in the rotor current layer after bar breakage is not confined to the bars in the region of the broken bar, and it evolves over time during the machine’s electrical cycle. Secondary increases appear in the current of bars at a distance approximately equal to the polar pitch of the machine. These secondary increases could be the cause of progressive damage at other points of the cage.
- Rotor asymmetries which involve a certain number of non contiguous broken bars produce a lower distortion in the rotor current layer than those where the same

faulty bars are adjacent. The attenuation effect caused by the distribution of the faulty bars is maximum when the bars are located under magnetic poles of different polarity. Moreover, the decrease caused in machine efficiency by the number of broken bar is less important if the bars are distributed along the rotor perimeter.

- The amplitude of the upper sideband of the current spectrum $(1+2s) f$ is not only related to the machine and torque speed ripple. In fact, the simulation carried out at a constant speed demonstrated its connection with the third order spatial flux density saturation in the airgap due to tooth saturation.
- Rotor asymmetries involving non-contiguous bars produce different values in the amplitudes of the current sidebands for use in rotor fault detection. In fact, lower sideband presents higher amplitude when the fault involves non-contiguous bars. This situation can lead to wrong evaluation of the real degree of failure present in the rotor.

Asymmetry in rotor current distribution was confirmed by analysing the degradation of faulty bars in two large induction machines. In these cases, one of the lateral faces of the bars had deeper damage to the surface than the other, which indicates the asymmetrical flux of the current. Moreover, this analysis also allows the prediction of asymmetrical flux of interbar current before and after failure.

[Watson 1999]: Watson, J.F.; Dorrell, D.G., "The use of finite element methods to improve techniques for the early detection of faults in 3-phase induction motors", Energy Conversion, IEEE Transaction on, Volume: 14 Issue: 3, Sept. 1999, Page(s): 655 –660.

This paper describes how commercial finite element packages may be used to simulate rotor faults and hence enhance the capability of practical condition monitoring schemes. Accurate models of the machine under faulted conditions are developed using both fixed mesh and time-stepping finite element packages. Some known causes of inaccuracy between models and experimental data are accounted for and the results of the simulation are compared with those obtained from a laboratory test rig. These models form the basis of a method to investigate fault types, which present condition-monitoring schemes, cannot detect.

The mechanisms which produce and affect the fault indicating sideband frequency components at $(1\pm 2s) f_0$ are very complex, however these mechanisms must be understood in order to advance present condition monitoring techniques. The simulation method described introduces the effects of speed ripple and rotor skew in an iterative attempt to improve the accuracy of the simulation. The use of a time-stepping finite element solver further confirmed the effects of the speed ripple, saturation and rotor skew on the fault indicating sideband frequency components of current. The model is now of sufficient accuracy to be used in the investigation of the effects of less common rotor faults such as broken end-rings and faults in double cage designs. A transient simulation technique is currently being developed which will be used in the investigation of these fault types.

[Kim 1997]: Chang-Eob Kim; Yong-Bae Jung; Sang-Baeck Yoon; Dal-Ho Im, "The fault diagnosis of rotor bars in squirrel cage induction motors by time-stepping finite

element method”, Magnetics, IEEE Transactions on, Volume: 33 Issue: 2 Part: 2, March 1997, Page(s): 2131 –2134.

This paper presents a fault diagnosis of the rotor bars in squirrel cage induction motors. The defective rotor bars such as broken bars and high resistance are detected by analysing the induced current in the coil caused by reluctance variation when the rotor is moving. In the analysis, the time stepping finite element method is used where the electromagnetic and circuit equations are coupled and the rotor movement is considered by automatic subdivision of air gap meshes. By the proposed method, various rotor fault conditions are simulated. The experimental results show that the analysis method is useful to detect rotor fault conditions.

[Henaio 1999]: H. Henaio, G.A. Capolino, M. Garcia-Melero, M-F. Cabanas, “A new model of the induction motor cage for diagnosis”, The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 383-388, 1999, Gijon, Spain.

The aim of this paper is to present a simplified model of a squirrel cage induction machine taking into account all space harmonics but neglecting all the mutual inductances between the rotor meshes. This simplification has the advantage to reduce the complexity of equations to be solved and mainly the coupling terms involving current derivatives. Then, a rotor mesh is reduced to a current controlled voltage source, resistances and leakage inductances. The comparison with the complete model is performed in order to show the improvements observed in the frequency domain when it is important to detect harmonics in presence of rotor faults. It can be shown that for the proposed model, the rotor mesh airgap flux spectrum is equivalent to the rotor mesh current spectrum in term of low frequency harmonics. The result is that the rotor fault influence can be reported in the axial flux, which is convenient for the detection with a low cost sensor.

In this paper, a new simplified model for a squirrel cage rotor has been proposed neglecting the mutual inductance between the rotor meshes. As it has been expected, the simplification did not affect the time domain analysis for the currents and the rotor flux magnitude. The theoretical proof has been giving us using the rotor mesh equations with simple circuit analysis. However, the result is more spectacular in the frequency domain even around the power supply frequency. The complete model produces large current pikes especially for the rotor mesh current and these spikes are practically removed using the simplified model. These fact permits to use either rotor mesh current or rotor mesh airgap flux to make a frequency domain analysis and this will be very useful in the case of fault detection using axial flux measurement.

The model is based on an equivalent circuit approach and it does not need many geometrical data from the machine manufacturer. On the stator side, only the number of slots, their shape and the way of winding the different phases are enough to build a model. On the rotor side, the number of slots, their shape and the ring geometry is useful to develop the proposed technique.

[Thomson 1998]: Thomson, W.T.; Barbour, A., “On-line current monitoring and application of a finite element method to predict the level of static airgap eccentricity

in three-phase induction motors”, Energy Conversion, IEEE Transaction on, Volume: 13 Issue: 4, Dec. 1998, Page(s): 347–357.

The introduction reviews the real practical problems of airgap eccentricity in large 3-phase induction motors. On-line monitoring methods for diagnosing airgap eccentricity are also discussed and a state of art review on the application of current monitoring to detect airgap eccentricity is presented. The limitations of the classical MMF and permeance wave approach for predicting the severity of airgap eccentricity are discussed. The time stepping finite element (FE) method and FFT analysis technique are used as “analyses tools” to predict the frequency components in the current (Hz and dB) as a function of static airgap eccentricity.

Excellent agreement is obtained between the measured and predicted frequency components (Hz) in the current spectra, which are a function of static eccentricity. The FE method is also used to predict the magnitude (dB) of these frequency components in the current spectrum with different levels of static airgap eccentricity. These predictions are much closer to the measured values in comparison to previous attempts using the classical MMF and permeance wave approach. The contents of this paper will be of particular interest in the manufacturers and industrial users of three-phase induction motors.

The time stepping FE method has accurately predicted the frequency components in the current spectrum which are a function of static airgap eccentricity and the simulations were verified by experimental results. Of particular importance is the application of the FE method to predict the magnitudes of these current components as a function of the degree of severity of static eccentricity. The results show that the analysis has produced a good estimate of their magnitudes in dB.

[Schoen 1995]: Schoen, R.R.; Habetler, T.G.; Kamran, F.; Bartfield, R.G., “Motor bearing damage detection using stator current monitoring”, Industry Applications, IEEE Transactions on, Volume: 31 Issue: 6, Nov.-Dec. 1995, Page(s): 1274–1279.

This paper addresses the application of motor current spectral analysis for the detection of rolling-element bearing damage in induction machines. Vibration monitoring of mechanical bearing frequencies is currently used to detect the presence of a fault condition. Since these mechanical vibrations are associated with variations in the physical air gap of the machine, the air gap flux density is modulated and stator currents are generated at predictable frequencies related to the electrical supply and vibrational frequencies. This paper takes the initial step of investigating the efficacy of current monitoring for bearing fault detection by correlating the relationship between vibration and current frequencies caused by incipient bearing failures. The bearing failure modes are reviewed and the characteristic bearing frequencies associated with the physical construction of the bearings are defined. The effects on the stator current spectrum are described and the related frequencies determined. This is an important result in the formulation of a fault detection scheme that monitors the stator currents. Experimental results, which show the vibration and current spectra of an induction machine with different bearing faults, are used to verify the relationship between the vibrational and current frequencies. The test results clearly illustrate that the stator current signature can be used to identify the presence of a bearing fault.

[Bonnett 1992]: Bonnett, A.H.; Soukup, G.C., "Cause and analysis of stator and rotor failures in three-phase squirrel-cage induction motors", Industry Applications, IEEE Transactions on, Volume: 28 Issue: 4, July-Aug. 1992, Page(s): 921–937.

The purpose of this paper is to identify the various causes of stator and rotor failures. A specific methodology is proposed to facilitate an accurate analysis of these failures. This paper excludes failures of the bearings and lubrication system. This paper is an update and an abridgement of the previous papers written by the authors and is referenced in the references for a more detailed presentation on the subject matter.

[Bonnett 1992-2]: Bonnett, A.H., "Cause and analysis of bearing failures in electrical motors", Petroleum and Chemical Industry Conference, 1992, Record of Conference Papers., Industry Applications Society 39th Annual, 1992, Page(s): 87 –95.

The purpose of this paper is to present a methodology to identify the cause of failure for anti-friction bearings used in electric motors.

There are numerous ways to go about failure analysis. The procedure proposed is a simple one that can be easily taught and communicated to employees with a wide range of skills and background. This type of analysis will usually lead to the quick elimination of those factors, which are not contributing to the failure. When the problem is reduced to the one or two most likely culprits, thoughtful analysis will usually lead to the correct conclusion. It is not one's brilliance, which leads to the truth; instead it is the ability to sort that, which is important from among all of the unrelated data available.

[Nandi 1999]: Nandi, S.; Toliyat, H.A., "Condition monitoring and fault diagnosis of electrical machines-a review", Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE, Volume: 1, 1999, Page(s): 197 -204 vol.1.

A brief review of bearing, stator, rotor and eccentricity related faults and their diagnosis has been presented in this paper. It is clear from various literatures that non-invasive motor current signature analysis (MCSA) is by far the most preferred technique to diagnose fault. However, theoretical analysis and modelling of machine faults are indeed necessary to distinguish the relevant frequency components from the others that may be present due to time harmonics, machine saturation, etc. Other techniques for fault detection such as axial flux based measurements, vibration analysis, etc. have been also discussed. A section on automated fault detection has also been included.

[Chari 1988]: Chari, M.V.K.; Bedrosian, G.; Fealey, J.A.; Sober, T.J.; Scheibel, J., "Incipient failure prediction of rotating electrical machinery by eddy current on-line monitoring method", Magnetics, IEEE Transactions on, Volume: 24 Issue: 6, Nov. 1988, Page(s): 2889 –2891.

An electromagnetic online monitoring system is described. Present crack detection and online monitoring techniques are briefly summarised, and the eddy current method is

discussed in further detail. Electromagnetic analysis for sensor development and optimisation, laboratory experiments to verify the flaw detection and imaging system, and demonstration of hardware for the integrated online monitoring system are reported.

[Nandi 1999]: S. Nandi, R. Bharadwaj, H. Toliyat, A. Parlos, "Simulation of a three phase induction motor with incipient rotor cage faults", The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 389-394, 1999, Gijon, Spain.

This paper evaluates through simulation the line current spectrum of an induction motor at the incipient stage of bar breakage. The model can also be extended to multiple, full-blown broken bar case. The speed and torque ripples caused by broken bars can also be studied. The rules and laws generated through such simulations can then be used in neural network based diagnostic tools. Results in case of complete broken bars are validated by FE calculations. Experimental results with up to 4 bars partially broken are presented.

The inductances used in the simulation are verified through finite element results. The simulated line current waveform contains all the expected current harmonic sidebands as reported in literature; thus establishing the correctness and utility of the simulation technique. Experimental results with up to four broken bars clearly show the increase in sideband components around the fundamental component of current and the speed harmonics. Though the sidebands around the higher time harmonics are observable in the simulation results, they did not show any significant change in the experimental results. Thus at least for small die-cast rotor machines, it appears to be more reliable to check the sidebands around fundamental and the related speed harmonics in case of suspected broken bar faults.

[Said 2000]: Said, M.S.N.; Benbouzid, M.E.H.; Benchaib, A., "Detection of broken bars in induction motors using an extended Kalman filter for rotor resistance sensorless estimation", Energy Conversion, IEEE Transaction on, Volume: 15 Issue: 1, March 2000, Page(s): 66 –70.

This paper deals with broken bars detection in induction motors. The hypothesis on which detection is based is that the apparent rotor resistance of an induction motor will increase when a rotor bar breaks. To detect broken bars, measurements of stator voltages and currents are processed by an extended Kalman filter for the speed and rotor resistance simultaneous estimation. In particular, rotor resistance is estimated and compared with its nominal value to detect broken bars. In the proposed extended Kalman filter approach, the state covariance matrix is adequacy weighted leading to a better state estimation dynamic. Its main advantage is the correct rotor resistance estimation even for an unloaded induction motor. As part of this estimation process, it is necessary to compensate for the thermal variation in the rotor resistance. Computer simulations, carried out for a 4 kW four-pole squirrel cage induction motor, provide an encouraging validation of the proposed sensorless broken bars detection technique.

[Kliman 1997]: Kliman, G.B.; Mazereeuw, J.G.; Patel, S.C., "Sensorless approach to on-line motor diagnostics", Cement Industry Technical Conference. 1997. XXXIX Conference Record., 1997 IEEE/PCA, 1997, Page(s): 135 –140.

Loss of process, reduced productivity, equipment damage, safety issues and life extension have driven continuing research in the area of non-invasive online motor diagnostics to recognise incipient failures and avoid the catastrophic results. Breakthroughs have been made utilising a variety of methods, which can be applied on today's cost-effective microprocessor hardware platforms to accurately diagnose impending failures of motors. These include failure modes involving bearings, broken bar or shorted turns, and abnormal shaft torque conditions. This paper describes the research, methodology and application of these technologies.

[Kliman 1997]: Kliman, G.B.; Premerlani, W.J.; Yazici, B.; Koegl, R.A.; Mazereeuw, J., "Sensorless, online motor diagnostics", IEEE Computer Applications in Power, Volume: 10 Issue: 2, April 1997, Page(s): 39 –43.

Early detection of abnormalities in electric motors helps to avoid expensive failures. Motor current signature analysis (MCSA) implemented in a computer-based motor monitor can contribute to such condition-based maintenance functions. Such a system may also detect an abnormality in the process as well as the motor. Extensive online monitoring of the motors can lead to greater plant availability, extended plant life, higher quality product, and smoother plant operation. With advances in digital technology over the last several years, adequate data processing capability is now available on cost-effective, microprocessor-based, protective-relay platforms to monitor motors for a variety of abnormalities in addition to the normal protection functions. Such multifunction monitors are displacing the multiplicity of electromechanical devices commonly applied for many years. Following some background information on motor monitoring, this article features recent developments in providing tools for the diagnosis of faults or incipient faults in electric motor drives, including: sensorless torque measurement; direct detection of turn-to-turn short circuits; detection of cracked or broken rotor bars; and detection of bearing deterioration.

[Natarajan 1989]: Natarajan, R. "Failure identification of induction motors by sensing unbalanced stator currents", Energy Conversion, IEEE Transaction on, Volume: 4 Issue: 4, Dec. 1989, Page(s): 585 –590.

A technique suitable for real-time failure monitoring of cage induction motors is presented. The proposed method utilises online sensing of the unbalance in the stator current signal to assess the integrity of the motor. This approach is extremely effective where the system neutral is high resistance grounded. The sensor is inexpensive, non-invasive, reliable, and easy to install. Instead of analysing the spectral components of the signal, the absolute magnitudes are used for identifying the incipient failure; therefore, the need for computing and data processing is partly eliminated. This method is tested for Wye connected motors. The results from laboratory investigations are presented. The usefulness of this approach is demonstrated with the aid of simulated fault conditions in the experimental motor. The efficacy of the proposed method in industrial power systems is discussed.

Conclusion: *A review of publications on MCSA, or diagnosis based on induction motors current passive analysis, reveals the ironic fact that there is an inverse relationship between the fault detection ease and the importance to the user of that fault detection. In fact, there are dozens of published papers on broken rotor bars and only two or three on the use of MCSA for bearing faults detection, in spite of several studies that show bearing faults to account for almost 50% of induction motor failures as opposed to around 10% for rotor cage problems [IAS 1985], [IAS 1987], [Thorsen 1995], [Kliman 1997].*

6. Fault detection methods using parameter estimation

[Moreau 1999]: S. Moreau, J.C Trigeassou, G. Champenois, J.P. Gaubert, "Diagnosis of induction machines: a procedure for electrical fault detection and localisation", The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 225-230, 1999, Gijon, Spain.

This article presents a diagnosis procedure for a squirrel cage induction machine based on parameter estimation through an output error algorithm, which is performed by taking into account prior information available on the safe system operating in nominal conditions. Thanks to a stator three-phase model of the machine, this procedure allows both detection and localisation of stator and rotor failures.

A diagnosis procedure for squirrel cage induction machines has been proposed and validated on real faulty experiments. Parameter estimation is used to perform fault detection and localisation (in the case of the stator). Stator/rotor fault localisation is performed by simple Fourier's analysis. This procedure seems to be well suited for industrial applications because it requires only a small disturbance operation.

The ultimate objective is to detect very small faults, like a short-circuit between two turns. Thus, it will be necessary to improve parameter estimation with a more appropriate model, not necessary more complex. For instance, it will be necessary to take into account iron losses, in order to limit their influence on stator and rotor resistances.

[Baghli 2001]: L. Baghli, H. Razik, A.Rezzoug, C. Caironi, L. Durantay, M. Akdim, " Broken bars diagnosis of 3600 rpm 750 kW induction motor. Comparison modelization and measurement of phase currents", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 237-241.

This paper deals with the modelling, simulation and experiments on a medium power induction motor, which has rotor faults. The model presented here is a transient model of a single cage induction motor. The detailed equations of the system are developed and explained as well as the electromagnetic parameters used. The model takes into

account rotor broken bars and end ring faults. The assumptions made and the method used to detect rotor faults are discussed. Tests have been performed on 3600 rpm – 750 kW induction motor with Chrome Copper squirrel cage intentionally damaged. The experiment methodology is presented in details. Time signals and FFT of phase currents and bearing vibrations are presented for significant rotor defects. Simulations using this model are compared to experiments on a medium power induction motor (750 kW).

The model used in the simulation gives interesting information to study the effect of rotor broken bars for a 750 kW 3600-rpm motor. However, the model must consider the real resistance distribution of rotor bars, which is the result of the bar resistance and the brazed interfaces. The model is improved by including multi-harmonics contributions to analyse precisely the phase current upper than the first side-bands order and in large band.

To discriminate the origin of the modulation effects, the expert must crosses the vibration analysis and the current analysis and works by comparison to the reference state of delivery of the shaft line after integration on-site. The use of FFT in large band of the signals issued from the measurement and simulation is relevant for the diagnostic purpose. For the current analysis the disadvantage comes from the difficulty of performing a FFT of the signal with sufficient precision to know exactly the amplitude of the sidebands. They pulse at low frequencies and are very close to the fundamental. Therefore the acquisition must be done over a long period, may be with a minimum of 16-bit of resolution for the A/D acquisition device.

With the experimental knowledge of defect gradation, Alstom Moteurs is able now to analyse very early broken bars process of degradation, and to check the quality of rotor assembly to be in accordance to severe specifications of vibration levels especially for petroleum and marine applications.

[Bachir 2001]: S. Bachir, S. Thani, J.C Trigeassou, G. Champenois, Induction motor modelling of broken rotor bars and fault detection by parameter estimation”, The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 145-150.

An original approach is presented in this paper to diagnosis broken rotor bars in squirrel cage induction motors. A new model based on the study electrical parameters is developed. We apply the Concordia transform on multi-loops squirrel cage motor to obtain defective rotor resistance according to healthy one. Thus, we introduce an additional parameter to explain rotor faults, which allows the calculation of the number of broken rotor bars.

Electrical and faulty parameters are obtained by off-line estimation technique through an output error algorithm. It is performed by taking into account prior information available on the safe system operating in nominal conditions. Thus, based on the stator dq currents, a new formulation of multivariable quadratic criterion is used in order to incorporate electrical parameter knowledge. Several faulty rotors are available to carry out experiments with a three-phase induction motor. Experimental results show that this procedure allows predictive failure detection.

The proposed model used for fault simulation gives interesting information to analyse the effect of broken rotor bars. The introduction of a faulty parameter in classical Park's model due to rotor resistance variation allows the detection of faults. Original methodology based on continuous parameter estimation with prior information is proposed. Experimental results exhibit the efficiency of this technique for on-line broken rotor bars diagnosis of induction motors under varying speed.

[Bachir 2001-2]: S. Bachir, S. Thani, J.C Trigeassou, T.Poinot, " Stator fault diagnosis in induction machines by parameter estimation", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 235-240.

In this paper, authors propose a new model of squirrel cage induction motors under stator faults. This model takes into account the effects of inter turn faults resulting in the shorting of one or more circuits of stator phase winding. The stator asymmetries caused in the faulty case are explained by the introduction of the short-circuit elements in the conventional Park's model. Each short-circuit element allows detection and the localisation of faults in the three stator windings.

A new diagnosis procedure based on parameter estimation of this faulty model is proposed. The estimation technique is performed with the help of prior information available on the safe system operating in nominal conditions. Experimental test results show the good agreement between the real faults and their estimations and demonstrate the detection and localisation capabilities of this predictive failure detection technique.

In this work, the feasibility of diagnosing shorted turns in the stator windings by parameter estimation with the help of a new faulty model of induction machine has been investigated. This model, very realistic is dedicated to stator faults simulation under varying speed. Off-line parameter estimation with appropriate integration of physical knowledge is used to perform fault detection and localisation.

Experimental tests illustrate the good approximation of real faults and efficiency of this technique for use in fault diagnosis. Thus, even in safe conditions, a proposed diagnosis procedure by parameter estimation gives a very realistic image of present unbalance in the machine. This is doubtless due on one hand, to the efficiency of estimation algorithm with introduction of prior information, and on the other hand to the developed transient model of induction motor dedicated to stator faults.

[Makki 1999]: Makki . A, Grellet G., Yahoui A., "Analytical model of saturated wound rotor synchronous motor with winding faults", The 1999 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, pp. 263-268, 1999, Gijon, Spain.

This paper studies the effect of stator winding faults on wound rotor synchronous motor performance. The studied stator faults are the short circuits of one stator phase and one section of a phase. The model uses a magnetic equivalent circuit model with saturation and space harmonics. To detect the faults a spectral analysis of the electromagnetic torque and of the rotor current was performed.

According to the results of the simulation, the two stator winding faults studied can be easily detected by spectral analysis of the motor torque and stator or rotor current by analysing the low and high frequency lines which differ sufficiently to operate a discrimination. But this must be validated by tests. This model allows studying not only the winding faults but also the magnetic circuit faults such as broken teeth or yoke and mechanical unbalances by air gap permeance modulation function. It can be used also, for machine simulations with digital command and control, instead of Park model, which neglects saturation and space harmonics.

5. Fault detection methods using partial discharge techniques

The drive to obtain improvements in plant economy, availability and useful operating life has led naturally to an increasing interest in the possibility of monitoring all aspects of machine condition whilst the plant is operating in normal service. On-line monitoring of discharge activity in the stator winding insulation structure can give a sensitive indication of degradation processes so long as individual discharge events are detected and measured. The discharge characteristic so obtained is that which the machine exhibits continuously in normal service and is influenced by service conditions such as physical movement which cannot be simulated in an off-line test. Regular monitoring provides the opportunity for early detection of problems and possible remedial action to prolong winding life, or for scheduling of rewind operations during routine shutdown periods.

Partial discharge tests can determine which motor and generator stator windings are experiencing insulation problems. A deteriorated winding has a PD activity, which can be 30 times or more higher than a winding in good condition. This great difference in PD activity enables even nonspecialized maintenance personnel to identify the few motors or generators in a company, which need further investigation and/or maintenance. There are several advantages to on-line partial discharge tests. Machines in good condition require less attention. The overall effect is lower maintenance costs. After implementing on-line partial discharge tests, as well as other monitoring such as flux probing or current harmonic analysis and improved temperature sensing, companies can often confidently extend the outage between major machine inspections. This saves on outage costs and reduces the risk of a stator fault due to human error during maintenance. Finally, on older machines, if there has been no increase in partial discharge activity over time, then the life of the stator winding can be confidently extended, saving a considerable capital expenditure.

Literature on partial discharge methods used in fault detection

[Edwards 1995]: Edwards, D.G., "On-line monitoring of high voltage stator windings", Condition Monitoring of Electrical Machines, IEE Colloquium on, 1995, Page(s): 2/1 -2/3

This paper describes an on-line discharge monitoring system, which has been extensively applied to machines in service, and presents case studies to illustrate the correlation between measured discharge characteristics and winding condition.

[Stone 1998]: Stone, G.; Kapler, J., “Stator winding monitoring”, IEEE Industry Applications Magazine, Volume: 4 Issue: 5, Sept.-Oct. 1998, Page(s): 15 –20.

This paper reviews the need for on-line monitoring and describes ozone, temperature and partial discharge monitoring systems. It was found that by combining temperature, ozone and partial discharge monitoring, almost all unexpected failures can be eliminated, and maintenance engineers can often plan corrective action at a fraction of the cost of a rewind.

[Cash 1998]: Cash, M.A.; Habetler, T.G.; Kliman, G.B., “Insulation failure prediction in AC machines using line-neutral voltages”, Industry Applications, IEEE Transactions on, Volume: 34 Issue: 6, Nov.-Dec. 1998, Page(s): 1234 –1239.

This paper presents a novel technique to detect insulation failure in polyphase AC machines. The machine must be star connected and have the neutral accessible. The mathematical theory of the technique is provided and supported by an experimental validation—turn faults in the stator of an induction machine are detected from the algebraic sum of the three instantaneous line-neutral voltages. However, this voltage sum contains undesirable frequencies that decrease the sensitivity of the scheme. Bandpass filtering the voltage sum (around the fundamental) optimises sensitivity by removing the harmonics that arise from core saturation, slot harmonics, etc. The design of the scheme makes it practically immune to false alarms attributable to varying load conditions, operating temperatures and source voltage perturbations. It is shown that this technique is simpler in both theory and practice than other techniques based upon accurate calculations of sequence voltages and currents. The simplicity of this technique permits a low-cost implementation to flag a turn fault within a few cycles of the fundamental machine excitation.

[Dymond 1998]: Dymond, J.H., “Sparking, electrical discharge, and heating in synchronous and induction machines: can it be controlled?”, Industry Applications, IEEE Transactions on, Volume: 34 Issue: 6, Nov.-Dec. 1998, Page(s): 1371 –1377.

It is impossible to eliminate all occurrences of sparking and localised heating from the interior of electric machines during the 20 to 40 years that they are normally in service. One can minimise the probability of sparking and localised heating by exercising precautions, which will eliminate or minimise the sources of these conditions in AC machines. Most new machines have a low probability of sparking but some design steps can be taken which condition the machine as a sparking type or a non-sparking type. The paper discusses the aspects of arcing between rotor and stator in the air gap, sparking between rotor parts, sparking between frame components, sparking due to broken or open bars and end rings and surface discharge on the stator winding. Also discussed is what action, if any can be taken in design, application and maintenance to eliminate or control these sparking problems.

[Stone 1995]: Stone, G.C.; Sedding, H.G., “In-service evaluation of motor and generator stator windings using partial discharge tests”, Industry Applications, IEEE Transactions on, Volume: 31 Issue: 2, March-April 1995, Page(s): 299 –303.

Partial discharges (corona) are a symptom of most types of deterioration of motor and generator stator windings rated 4 kV and above. Experience indicates that partial discharges occur years before failure. This leaves sufficient time to plan corrective maintenance to avoid the in-service failure of the motor or generator. This paper describes a new type of partial discharge test, which can be performed by plant personnel during normal operation of the machine, thus enabling all users of large machines to plan maintenance. The key requirement of the new test is to remove all the interference caused by other sparking and discharging sources in a plant. Such noise has led to false indications of stator winding deterioration in the past. The new test uses high-voltage capacitive sensors, high-frequency current transformers, or 1000 MHz electromagnetic couplers to detect the discharge signals. These signals are processed on a pulse-by-pulse basis by a specialised electronic instrument to remove noise and the remaining partial discharges are then categorised according to number, magnitude, and phase position. The test has been implemented on over 100 machines, and the results appear promising.

[Zhu 2000]: Zhu, H.; Green, V.; Huynh, D.; Ravenscroft, L., “How to identify stator insulation problems using on-line partial discharge analysis”, Electrical Insulation, 1999. Conference Record of the 2000 IEEE International Symposium on, 2000, Page(s): 506 –511.

On-line partial discharge (PD) testing of the stator winding of hydro generators, turbine generators, and large motors has been performed for half a century. However, questions remain on how to best use PD data to identify stator insulation problems. This paper analyses why one cannot rely on an absolute PD magnitude to assess the insulation condition of rotating machines. Some of the factors, which affect the diagnosis of stator insulation problems, include the following: 1) PD calibration problems in rotating machines; 2) Bandwidth of the PD detector; 3) PD types and locations; 4) Differences among machines and PD measurements. The paper describes how these factors influence the assessment of stator insulation condition. PD trend analysis is recommended as the best way to identify machine insulation problems and is well demonstrated by some case studies. Precautions in using a PD database to assess the likelihood of insulation failures are given. The paper concludes that a significant increase in PD activity within a certain period of time is a sign of severe insulation deterioration.

[Contin 2000]: Contin, A.; Cavallini, A.; Montanari, G.C.; Puletli, F., “A novel technique for the identification of defects in stator bar insulation systems by partial discharge measurements”, Electrical Insulation, 1999. Conference Record of the 2000 IEEE International Symposium on, 2000, Page(s): 501 –505.

Results of investigations performed in order to improve the current diagnostic techniques used for the evaluation of insulation systems of AC rotating machine stator windings are presented. Improvements come from the development of a new measuring system and the stochastic analysis of partial discharge (PD) pulse signals. The

measuring system allows the digital acquisition of PD-pulse signals, operates at a sampling rate high enough to avoid frequency aliasing and provides an amount of PD-pulses, which enables PD stochastic analysis. In addition to the traditional PD-pulse height and phase analysis, PD-pulse shape processing is also available. The first results of PD measurements performed on different types of complete stator bars, with and without defects, are reported to show the system performance.

6. Fault detection methods using shaft voltage information

What is Shaft Condition Monitoring?

A continuous monitoring technology that uses shaft current and voltage profiles in operating units to determine if there are developing problems, or existing problems in electrical and non-electrical rotating machinery.

Benefits of Shaft Condition Monitoring:

Shaft Condition Monitoring offers a means to prevent costly parts replacement from not only shaft current damage, such as frosting, pitting and spark tracking, but of other more serious failures as well.

Many Case Histories have been reported, confirming the detection power of this new CBM technology.

- Shaft Rubs
- Loss of Shaft Grounding
- Torn Copper Leaf Causing Intermittent Ground Fault
- Loss of Shorts in Insulation at Bearings, Seals and Couplings

Shaft Condition Monitoring techniques yield “Early Warning” which empowers maintenance personnel to catch the onset of problems and determine incipient failures, long before their effect is made known by temperature and vibration sensors.

The most common signs of shaft current damage (sometimes referred to as electromagnetic discharge) are frosting, pitting or spark tracks on bearings, collars, journals and even shafts. This type of damage is often passed off as mechanical wear, and the typical solution is to incur the cost and replace the damaged parts. If these parts are instead repaired and sent for machining, more residual magnetism may be introduced, causing more severe damage visible only at the next shutdown. In some machines with shaft current problems, the loss of material can be so severe that there is radial or axial movement of the shaft. Proximity probes may register high peaks caused by the presence of high magnetic fields, which can be incorrectly identified as electrical runout or as vibration harmonics. One machine vendor, after trying typical solutions, such as replacing oil, balancing, adding probes with monitoring, finally described the machine as having "mysterious mechanical damage."

After many years of investigating shaft currents, many companies have found that no two machines have shown identical symptoms and signs. If a machine has continued problems of varying nature, shaft currents may be a factor. Shaft currents should only be ruled out after a thorough magnetic survey, and shaft voltage and current analysis have been completed.

Literature on the shaft monitoring techniques used in fault detection and condition monitoring

[Costello 1993]: Costello, M.J., "Shaft voltages and rotating machinery", Industry Applications, IEEE Transactions on, Volume: 29 Issue: 2, March-April 1993, Page(s): 419 –426.

In order to determine whether a machine is experiencing shaft voltage and current problems, recognition of the four types of damage is imperative. The four distinct types of shaft current damage, frosting, spark tracks, pitting, and welding is described. The four shaft voltage sources and their means of generation are discussed in detail. Methods for correction and/or elimination of these sources are reviewed, so that user can better understand how these voltages and currents are generated. Tests for the detection of shaft voltage sources and their potential circuits are outlined. The most promising, by far, in terms of identifying the potential voltage source, is the direct measurement of shaft voltage and currents. It appears that even though certain assumptions are necessary in this method of testing and analysis, when these measurements are combined with an adequate background of electrical theory, they are extremely useful in determining the health of the train with regards to circulating currents.

[Ong 2001]: Ong, R.; Dymond, J.H.; Findlay, R.D.; Szabados, B., "Shaft current in AC induction machine-an online monitoring system and prediction rules", Industry Applications, IEEE Transactions on, Volume: 37 Issue: 4, July-Aug. 2001, Page(s): 1189 –1196.

This paper looks at a system for online shaft current monitoring. The proposed method of shaft current monitoring is non-invasive, reliable, portable, and low cost. Causes of the shaft current are described and prediction rules introduced. Fault conditions such as air-gap eccentricity, slot harmonics, and rotor broken bars or end ring result in asymmetrical flux pattern around the shaft, hence, resulting in shaft voltage. Bearing failures can occur when the voltage level exceeds the threshold of the oil film. The importance of the oil film is described.

An accurate non-invasive method of determining the fault mechanisms causing the presence of shaft current was presented. The Rogowski coil is of the air-core type and is not subjected to permeability variation and saturation, which can affect measurement accuracy. Furthermore, stray flux, which can affects measurement accuracy had been minimised. The Rogowski coil method allows for online monitoring of the bearing system and its insulation system.

The effect of air-gap eccentricity on the magnitude of the shaft current is less as the poles of the machine increase. The joints between the lamination segments and saturation are the fault mechanisms causing the shaft current in the eight-pole induction machine. Saturation of the tooth accentuates the magnitude of the shaft current. The importance of the oil ring to deliver a sufficient amount of oil to the bearing is demonstrated.

[Ong 1997]: Ong, R.; Dymond, J.H.; Findlay, R.D., "Comparison of techniques for measurement of shaft currents in rotating machines", Energy Conversion, IEEE Transaction on, Volume: 12 Issue: 4, Dec. 1997, Page(s): 363 –367.

Irregularities in the magnetic circuits of motors may result in spurious voltages that lead to shaft currents through the shaft, bearings, bearing supports and closing through the machine framework. The IEEE Standard Test Procedure for Polyphase Induction Motors and Generators discusses the shaft current and presents a measurement method for recording either the voltage across the ends of the shaft or the current. This paper discusses an alternative measurement approach and its application to the identification of shaft current in a large induction machine. Procedures were developed for measuring the shaft current. The procedures include the shunt current method and the measurement using the Rogowski coil. Only the Rogowski coil measurement yields accurate measurements of shaft currents whereas the other method either yields inaccurate measurement or may result in other problems for the machine's integrity. The theory and justification for the superiority of the Rogowski coil method is presented along with supporting test data.

[Wang 2000]: Changting Wang; Gao, R.X., "Sensor placement strategy for in-situ bearing defect detection", Instrumentation and Measurement Technology Conference, 2000. IMTC 2000. Proceedings of the 17th IEEE, Volume: 3, 2000, Page(s): 1463 –1467.

The placement of sensors is of critical importance to achieving high quality measurement for machine condition monitoring and fault diagnosis. This paper investigates sensor placement strategy for detecting structural defects of a ball bearing. Based on an analytical study of signal propagation from the defect location to the sensors, numerical simulations using a finite element algorithm were conducted to validate the signal strength at several representative sensor locations. The results were then experimentally verified through actual measurements. The study has shown that to achieve a high signal-to-noise ratio, the sensors need to be placed as closely as possible to the bearing, where signals due to structural defects are generated. The study has provided a theoretical framework for designing sensor-embedded bearings with built-in diagnostic capabilities.

For bearing condition monitoring, a sensor placed near or within the bearing to be monitored enables too much higher signal-to-noise (S/N) ratio as compared to other sensor locations. This finding agrees with the theoretical analysis, and has been verified both numerically through finite element analysis and experimentally through actual bearing measurements. Compared to "external" sensors, a bearing embedded sensor suffers the least from signal losses along the propagation paths, and is best protected from exposures to background vibrations. In addition, it has the advantage of

pinpointing the exact location of a defective bearing when multiple bearings are involved in a machine system. This can be specifically valuable to real-time, in-situ condition monitoring of critical bearings.

[Bowers 2001]: S.V Bowers, K.R Piety, " Proactive motor monitoring through temperature, shaft current and magnetic flux measurements", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 569-578.

Proactive motor monitoring methods can be employed to avoid premature failures as well as provide additional sensitivity to electrically generated faults. These proactive measurements which can be very beneficial are temperature, flux and shaft current. Abnormal temperatures can point to several potential problems such as: overheating due to poor airflow or unbalanced voltage, bearing failure, and even degradation in the rotor and stator. A flux coil is employed to capture flux signals, which provide an electrical "quality" signature sensitive to conditions, which alter the electrical characteristics of the motor, such as broken rotor bars, eccentricity, imbalance between phases and stator faults. Shaft current measurements detect unwanted stray currents, which are a root cause associated with premature bearing failures.

An in-depth discussion and description of these measurements were presented in [Bowers 1993]. Highlights of that paper are presented below along with case histories illustrating the proactive and predictive "power" of monitoring technologies.

Temperature, magnetic flux and shaft current measurements can be conveniently collected, in less than 5 minutes per motor, with a portable vibration data collector. Excessive heat is the main factor responsible for shortening the life of motors. Heat mostly affects the life of the insulation system and bearings. Therefore trending temperature (or a normalised thermal parameter) can provide early indication of premature degradation. The magnetic flux for a given motor varies with changes in the electrical characteristics. The spectra of magnetic flux measurements can indicate electrically related faults as well as motor speed. The speed can then be used to calculate a relative value for load, which is used to determine a normalised thermal parameter. The presence of shaft currents will cause bearings to prematurely fail. A shaft brush (whisker) is a simple sensor capable of measuring such currents. By knowing excessive shaft currents are present, maintenance can be performed to eliminate premature bearing failure due to such currents.

In summary, temperature, axial flux and shaft current measurements protect the motor against fault conditions, which previously were difficult or impossible to detect with other on-line technologies. In an effort to develop better instrumentation and improve analysis techniques, several industrial sites are involved in research with the authors. Upon successful conclusion of this research, the ultimate result will be decreased downtime and increased savings.

[Stefanko 2001]: S. Stefanko, I. Kurtovic, M. Bogut, M. Kovacevic, " Broken rotor bar detection in induction machines using measurement of shaft currents", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 623-626.

It is well known that magnetic asymmetries can result in a shaft current of the induction machine. This current can be measured with coil installed around the shaft. It will be shown that also a broken bar of squirrel-cage can affect the increase of shaft current and appearance of frequencies $(1\pm 2s) f$ in the current-spectrum. The tested machine was a 37 kW, 6-pole induction motor.

Characteristic changes of waveforms and frequency spectrum of stator current, bearing vibrations and shaft current have been found in an experimental investigation of broken squirrel-cage of an induction motor. It is proven by experiments that shaft currents can be produced both by asymmetries of the magnetic flux of the motor and by electrical asymmetries (broken squirrel-cage) as well. Characteristic frequencies $(1\pm 2s) f$ appear both in the shaft and in the stator currents.

The diagnostics of broken squirrel-cage is based on recognition of characteristic frequencies that vary with variations of speed of rotation, i.e. with variations of slip. The diagnostics requires frequency analysers having the resolution of harmonics with distance that equals double slip frequency and that distance can be very small in large machines or in the machines that are not rated loaded.

7. Literature on industrial experience on fault detection methods

[Smith 1999]: Smith, R., "Monitoring for rotor shorted turns", Understanding your Condition Monitoring (Ref. No. 1999/117), IEE Colloquium on, 1999, Page(s): 811–820.

The paper describes the Siemens (formerly Parsons') Rotor Shorted Turn Monitor (RSTM). The monitor was developed in the early 1990s for application to large steam turbine driven generator rotors. At the heart of the RSTM is a mathematical algorithm, which processes the signal from a search coil located in the air-gap. This analysis program is called in sequence for 1 to 4 generators by a supervisory program, which records the results and presents them, in a variety of forms, to a PC screen. Many results were collected from one of the first RSTMs to be placed in service at an UK power station having rotors with a history of shorted turn indications. From these it was possible to assess the effectiveness on the analysis program in coping with the influence of magnetic saturation in the rotor teeth over a wide range of load. The paper also outlines alternative methods for detecting shorted turns, their causes and the case for continuous monitoring.

[Burbidge 1995]: Burbidge, R.M., "On-line monitoring of stator winding insulation-the manufacturer and service engineer's view", Condition Monitoring of Electrical Machines, IEE Colloquium on, 1995, Page(s): 4/1 -4/2.

GEC Alstom helped to pioneer the installation of monitoring systems based on capacitive couplers in the UK and has now been engaged in this field of work for over ten years. Many industries and utilities regard on-line monitoring of stator winding insulation as important. This is especially true of those operating hydroelectric

generators and critical rotating machines on oil platforms. Electrical machine operators in other continuous process industries are also now using this form of monitoring. The author briefly discusses on-line monitoring techniques, including partial discharge measurement, and their benefits to users.

[Baghli 2001]: L. Baghli, H. Razik, A.Rezzoug, C. Caironi, L.Durantay, M. Akdim, ” Broken bars diagnosis of 3600 rpm 750 kW induction motor. Comparison modelization and measurement of phase currents”, The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 237-241.

This paper deals with the modelling, simulation and experiments on a medium power induction motor, which have rotor faults. The model presented here is a transient model of a single cage induction motor. The detailed equations of the system are developed and explained as well as the electromagnetic parameters used. The model takes into account rotor broken bars and end ring faults. The assumptions made and the method used to detect rotor faults are discussed. Tests have been performed on 3600 rpm – 750 kW induction motor with Chrome Copper squirrel cage intentionally damaged. The experiment methodology is presented in details. Time signals and FFT of phase currents and bearing vibrations are presented for significant rotor defects. Simulations using this model are compared to experiments on a medium power induction motor (750 kW).

The model used in the simulation gives interesting information to study the effect of broken rotor bars for a 750 kW 3600-rpm motor. However, the model must consider the real resistance distribution of rotor bars, which is the result of the bar resistance and the brazed interfaces. The model is improved by including multi-harmonics contributions to analyse precisely the phase current upper than the first side-bands order and in large band.

To discriminate the origin of the modulation effects, the expert must crosses the vibration analysis and the current analysis and works by comparison to the reference state of delivery of the shaft line after integration on-site. The use of FFT in large band of the signals issued from the measurement and simulation is relevant for the diagnostic purpose. For the current analysis, the disadvantage comes from the difficulty of performing a FFT of the signal with sufficient precision to know exactly the amplitude of the sidebands. They pulse at low frequencies and are very close to the fundamental. Therefore the acquisition must be done over a long period, may be with a minimum of 16-bit of resolution for the A/D acquisition device.

With the experimental knowledge of defects gradation, Alstom Moteurs is able now to analyse very early broken bars process of degradation, and to check the quality of rotor assembly to be in accordance to severe specifications of vibration levels especially for petroleum and marine applications.

[Dal Mut 2001]: G. Dal Mut, A. Oldrati, E.Tortello, ” Monitoring and diagnostics in electrical machinery: and industrial experience”, The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 19-26.

Recent philosophy has pushed utilities and operators moving from planned maintenance to the predictive one and also full maintenance has gained an important role in operating power plants; as a consequence, the most important manufacturers are usually in the forefront also in this new approach. Moving from planned to predictive maintenance calls for efficient monitoring and diagnostics apparatuses/systems ("on-line and "off-line") also for electrical generators.

Description of the most popular of these systems is the major goal of the paper. Experimental and field figures are given too. Experiences in construction and commissioning show the capability of Ansaldo to tackle diagnostic problems, both for on-line and off-line applications. It is a common practice for Ansaldo to get diagnostics products from the market, if already developed and of a good reputation, in order to meet customer's requirements.

[Capolino 2001]: G.A. Capolino, H. Henao, G. Cirrincione, R. Grissel, T. Assaf, G. Ekwe, " Monitoring and diagnosis of induction machines in the University of Picardie: present and future", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 111-117.

This paper presents the actual status and some future developments of a research program on monitoring and diagnosis of AC electrical machines in the Department of El .Eng at the University of Picardie, Amiens. Started more than ten years ago with parameter identification and time-domain analysis, the program has progressively moved towards complex modelling of fault-related phenomena and frequency-domain analysis. At the beginning of the 21st century, co-operative research is on progress and it is suspected that sharing data and experiments on the web will be really possible in the near future. This will open the new concept of virtual laboratory in the field of electrical machines and electrical drives.

[Tallam 2001]: R.M Tallam, T.G Habetler, R.G Harley, " Limitations of model-based methods for electric machine condition monitoring", The 2001 IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, September 1-3, 2001, Grado, Italy, pp. 361-366.

The recent trend in condition monitoring is towards sensorless methods that use only terminal currents to monitor the health of the machine. Many schemes rely entirely on mathematical models of ideal machines, neglecting the effects of non-idealities in a real machine. Consequently, such schemes cannot reliably detect a fault at an early stage. In this paper, a survey on model-based methods for detection of commonly occurring faults in induction machines is presented, and their limitations are explained. In addition, methods that use artificial intelligence (AI) and other compensation techniques, to enhance the performance of fault detection schemes, are also presented.

A comprehensive survey of model-based methods for detection of stator winding turn faults, broken rotor bars, air-gap eccentricity and bearing faults, and temperature monitoring has been presented in this paper. Models cannot be entirely relief on for fault diagnosis, particularly for setting fault thresholds, since several sources of

asymmetries and non-idealities cannot be represented in a model. Hence, complicated machine-specific models have limited use for fault diagnosis; generic models can be used to derive fault signatures and compensation techniques for the effects of non-idealities.

For electrical faults, it is possible to compensate for model uncertainties using AI techniques or look-up-table based methods. If a particular AI technique requires data under fault conditions for training, simulated data cannot be used, since the reliability of the scheme would be limited by the errors in the model. Detection of eccentricity, broken bars and bearing faults requires baseline measurements to be made on motors, on an individual basis, to determine a fault threshold.

Resistance-based temperature estimation is an effective method to monitor the average winding temperature. Only the dc-injection scheme provides a reliable stator resistance estimate, as other model-based methods are sensitive to parameter errors and non-idealities.

[Carvalho 1998]: Carvalho, J.M.N.; Ribeiro, P.M.P.; Goncalves, M.; Cardoso, A.J.M., "The use of an unified diagnostic approach to predict the operating deterioration of three-phase induction motors", Power Station Maintenance - Profitability Through Reliability, 1998. First IEE/IMEchE International Conference on (Conf. Publ. No. 452), On page(s): 157 – 160, 30 March-1 April 1998

There are different techniques such as those based on the spectral analysis of frame vibration, spectral analysis of the stator current and spectral analysis of axial magnetic flux. Those are the most common techniques used in on-line diagnostic systems on the market.

Pego Power Station (Portugal) has chosen two on-line diagnostic systems; one based on spectral analysis of frame vibration and another based on spectral analysis of the stator current. Furthermore, a different technique based on the use of the Park's vector approach is being applied for diagnosing airgap eccentricity, rotor cage faults and stator winding interturn short circuits.

In this paper, a great emphasis will be given to Park's vector approach, since the other two diagnostic techniques based on the spectral analysis of frame vibration and spectral analysis of the stator current are already widely known. The paper highlights the advantages of using not only one, but different diagnostic systems, in order to effectively predict the operating deterioration of three-phase induction motors in a way that is both much more reliable and convincing than that one resulting from each different strategy when used alone. A special focus was given on the use of the Park's Vector Approach.

[Thomson 1999]: Thomson, W.T.; Barbour, A., "An industrial case study of on-line current monitoring and finite element analysis to diagnose airgap eccentricity problems in large high voltage 3-phase induction motors", Electrical Machines and Drives, 1999. Ninth International Conference on (Conf. Publ. No. 468), 1999, Page(s): 242 –246.

The on-site case history confirms that on-line current monitoring can diagnose abnormal levels of airgap eccentricity in large induction motors. The time stepping FE-predictions have confirmed previously observed experimental phenomena. The FE analysis has to be done off-line due to the computing power required but the predictor curves can be subsequently included into an on-line current monitoring system such that the degree of severity of airgap eccentricity can now be estimated and load conditions can be simulated.

[Bellini 2000]: Bellini, A.; Filippetti, F.; Franceschini, G.; Tassoni, C.; Passaglia, R.; Saottini, M.; Tontini, G.; Giovannini, M.; Rossi, A., "ENEL's experience with on-line diagnosis of large induction motors cage failures", Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, Volume: 1, 2000 Page(s): 492 -498 vol.1

The experience gained by ENEL on monitoring large induction motor's cage condition is reported in this paper. The diagnostic procedure is based on the motor current signature analysis (MCSA) and in particular on the two sideband current components near the frequency fundamental line that appear in the current power spectrum when a rotor bar/ring breakage occurs. According to the developed procedure, a diagnostic index obtained from these components is stored and its trend as a function of time allows detection of the occurrence of a failure in most cases. This event is clearly shown by the overcoming of a prefixed and triggered threshold. Moreover, machines with particular rotor magnetic structure are considered. In this case, unexpectedly high sideband components appear even in the presence of healthy cages, and the test procedure was adapted to account for these conditions.

The diagnostic procedure aimed at detecting rotor bar breakage in cage induction motors has been reviewed. It relies on the analysis of the stator current spectrum. Specifically the sum of the sideband components around the supply frequency produced by electric asymmetry is used as the diagnostic index.

This method was implemented in LabView environment thus resulting in a powerful and user friendly diagnostic tool. The effectiveness of this diagnostic method has been confirmed by laboratory tests at CESI and by on-field diagnosis of thermal power plants MW induction motors, performed by ENEL with the proposed tools.

Tests performed on motors with "spidered" rotor structure having the same number of legs and poles have shown high values of the selected diagnostic index even in absence of cage failures. In order to solve the above mentioned problem a criterion to distinguish the effect of cage electric failures from that caused by the magnetic structure has been recently studied and a suitable option has been introduced in the diagnostic tool.

[Sottile 2000]: Sottile, J.; Trutt, F.C.; Kohler, J.L., "Experimental investigation of on-line methods for incipient fault detection in induction motors", Industry Applications Conference, 2000. Conference Record of the 2000 IEEE, Volume: 4, 2000. Page(s): 2682 -2687.

Condition-based maintenance (CBM) of industrial equipment is generally recognised as being the most cost-effective means for improving equipment availability. However, prerequisite to successful implementation of CBM is a reliable detector of failing components. One such detector, termed the effective negative-sequence impedance, had previously been identified as an indicator of induction motor stator winding degradation. However, a limitation of this detector is that it does not change in a predictable manner under certain motor operating conditions. This paper presents an experimental investigation of an improved technique for online detection of induction motor stator winding degradation. The paper begins with a brief description of the detectors, followed by a detailed description of the experimental set-up; the experiments conducted and result.

Results from the experiments are very encouraging. Both of the mismatch predictors are sensitive to the stator deterioration that was simulated, their performance is not affected by supply unbalances or inherent machine/monitoring system asymmetry, and changes in them appear to be indicative of level of deterioration severity. In addition, no special sensors or calibration procedures were required to obtain these results. The negative-sequence voltage mismatch predictor appears to be slightly more sensitive to increasing deterioration severity; however, the absolute changes in the positive sequence mismatch predictor are larger.

[Bucci 1994]: Bucci, G.; Cecati, C.; Landi, C., "Special measurement system for on-line fault diagnosis of induction motors", Industrial Electronics, Control and Instrumentation, 1994. IECON '94., 20th International Conference on, Volume: 3, 1994, Page(s): 1794 –1798, vol.3.

In this paper, a special measurement system suitable for on-line fault diagnosis on dynamic systems is presented. The proposed system, employing an array of processors, is interfaced with the process by means of a special data acquisition unit. Due to its high throughput, it can be successfully used in many industrial plants and devices, including those requiring very short diagnosis times such as electrical drives. Fault detection and localisation are obtained by adopting a model-based method using a bank of fault detection filters. First results regarding the diagnosis of an induction motor are presented, and the main problems encountered with such an application are analysed and discussed.

It appears to be very efficient for the application of fault detection algorithms based on the adoption of a bank of filters and it can be successfully employed in many industrial fields. The system detects a failure through parameter estimation and localises it through statistical analysis of their variations. The first results in the case of an induction motor, obtained by simulation data appear to confirm the effectiveness of the proposed system and encourage the research program.

8. Conclusions

In general, condition-monitoring schemes have concentrated on sensing specific failure modes in one of three induction motor components: the stator, the rotor, or the bearings.

Even though thermal and vibration monitoring have been utilised for decades, most of the recent research has been directed toward electrical monitoring of the motor with emphasis on inspecting the stator current of the motor. In particular, a large amount of research has been directed toward using the stator current spectrum to sense rotor faults associated with broken rotor bars and mechanical unbalance.

All of the presently available techniques require the user to have some degree of expertise in order to distinguish a normal operating condition from a potential failure mode. This is because the monitored spectral components (either vibration or current) can result from a number of sources, including those related to normal operating conditions. This requirement is even more acute when analysing the current spectrum of an induction motor since a multitude of harmonics exist due to both the design and construction of the motor and the variation in the load torque. However, variations in the load torque, which are not related to the health of the motor typically, have exactly the same effect on the load current. Therefore, systems to eliminate induction motors arbitrary load effects in current-based monitoring have been proposed.

Motor current signature analysis (MCSA) is a non-invasive, online monitoring technique for the diagnosis of problems in induction motors. The industrial case histories have clearly demonstrated that MCSA is a powerful technique for monitoring the health of three-phase induction motors. The MCSA techniques utilise the results of spectral analysis of the stator current. Sometimes, reliable interpretation of the spectra is difficult, since distortions of the current waveform caused by the abnormalities in the drive system are usually minute. In this situation, an alternate medium for the motor signature analysis, namely the instantaneous power, is used. By theoretical analysis, computer simulations, and laboratory experiments, it is shown that the instantaneous power carries more information than the current itself. Utilisation of the instantaneous power is thus enhancing the reliability of diagnostics of induction motor drives.

A review of publications on MCSA, or diagnosis based on induction motors current passive analysis, reveals the ironic fact that there is an inverse relationship between the fault detection ease and the importance to the user of that fault detection. In fact, there are dozens of published papers on broken rotor bars and only two or three on the use of MCSA for bearing faults detection, in spite of several studies that show bearing faults to account for almost 50% of induction motor failures as opposed to around 10% for rotor cage problems.

Experimental results, which show the vibration and current spectra of an induction machine with different bearing faults, have been used to verify the relationship between the vibrational and current frequencies. The test results clearly illustrate that the stator current signature can be used to identify the presence of a bearing fault.

It was found that using simple system, induction machine, and high order spectra (HOS) theory it is possible to construct a general and robust method of determining the health of induction machines. Thorough experimental analysis being conducted have verified the theoretical approach, and demonstrated the versatility of such techniques.

Fault conditions such as air-gap eccentricity, slot harmonics, and rotor broken bars or end ring result in asymmetrical flux pattern around the shaft, hence, resulting in shaft voltage. After many years of investigating shaft currents, many companies have found that no two machines have shown identical symptoms and signs. If a machine has

continued problems of varying nature, shaft currents may be a factor. Shaft currents should only be ruled out after a thorough magnetic survey, and shaft voltage and current analysis have been completed. The method of shaft current monitoring is non-invasive, reliable, portable, and low cost.

Partial discharge tests can determine which motor and generator stator windings are experiencing insulation problems. A deteriorated winding has a PD activity, which can be 30 times or more higher than a winding in good condition. This great difference in PD activity enables even nonspecialized maintenance personnel to identify the few motors or generators in a company, which need further investigation and/or maintenance. There are several advantages to on-line partial discharge tests. Machines in good condition require less attention. The overall effect is lower maintenance costs. After implementing on-line partial discharge tests, as well as other monitoring such as flux probing or current harmonic analysis and improved temperature sensing, companies can often confidently extend the outage between major machine inspections. This saves on outage costs and reduces the risk of a stator fault due to human error during maintenance. Finally, on older machines, if there has been no increase in partial discharge activity over time, then the life of the stator winding can be confidently extended, saving a considerable capital expenditure.

The advantages of using wavelet techniques for fault monitoring and diagnosis of induction motors is increasing because these techniques allow us to perform stator current signal analysis during transients. The wavelet technique can be used for a localised analysis in the time-frequency or time-scale domain. It is then a powerful tool for condition monitoring and fault diagnosis.

Although current monitoring techniques are widely used in industry due to their success in the detection of broken rotor bars and their ability to report findings in a non-technical format, these systems do inherently have drawbacks. In order to facilitate successful detection of rotor faults during steady state operation a large supply current is required to flow. The large current usually being obtained by monitoring the motor whilst running under full load conditions. The necessity of requiring a large current in some cases may not be appropriate or achievable if, for example, the motor has been taken off line or removed to a workshop environment. In addition to requiring a large current these monitoring techniques also have difficulty in detecting other common rotor faults over and above simple broken bars. These faults include damaged end rings or broken bars within a double bar rotor machine. In reply to this, work was initiated to investigate the possibility of utilising the large supply current, which flows during the initial acceleration period of the motor at start-up. It was hoped that this transient current would yield the relevant health information and perhaps is capable of detecting other rotor faults without the necessity of the motor being operated under full load conditions.

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