On-line Fault Diagnostics of Three Phase Squirrel Cage Induction Motor Based on Motor Current Signature Analysis Method

By

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Thesis Submitted in Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

January 2012

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING
UNIVERSITI SAINS MALAYSIA

Acknowledgement

Praise is to Allah, the Most Gracious and the Most Merciful; from HIM, I got the health, the courage and the patience to complete this thesis. I would like to express my sincere gratitude to my supervisor Dr. Dahaman Ishak for his support and encouragement during the development of this research. I am thankful for his kindness and willingness in giving me his help. I would like to special thanks to Dr. Mohammad Kamarol Mohad Jamil for his willingness to assist in my research and also to our dean Prof Mohd Zaid Abdullah.

I would like to express my appreciation to all technicians in School of Electrical and Electronic Engineering, USM, for their assistance during my project testing and experiments.

I would also like to thank my lovely family especially my wife for her support and motivation during this time, and also for my young boys Mustafa and Hamza and my small daughters Salsabel and Tartel for their smiles. I would also like to thank my brothers and sisters for their encouragement during my university study. I would like to thank my friend Mohd Shawal Jadin for his support; finally I would like to thank all my friends at USM.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A, B, C	Stator phases (AC drive)
A/D	Analogue/Digital
AC	Alternative Current
B	Flux density (T)
CT	Current Transformer
DAQ	Data Acquisition
DAWT	Discrete Approximation Wavelet Transform
DC	Direct Current
f_s	Supply frequency (Hz)
f_b	Frequency of broken rotor bar
f_{ec}	Frequency components air gap eccentricity(Hz)
FEM	Finite Element Method
FFT	Fast Fourier Transform
f_r	Rotational speed frequency of the rotor (Hz)
g	Air gap length
H	Magnetic field strength (A-t/m)
HV	High voltage
I	Rated current
IEC	International Electro technical Commission
k'	Wavelength of the harmonic
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
L_{bar}	Inductance of a single bar
l_{bar}	Length of a rotor bar
L_{ring}	Inductance of a single ring
l_{ring}	Length of a single ring
m	Harmonic number
MCSA	Motor Current Signature Analysis
MMF	Magnetic Motive Force
m_r	Phase number of the rotor
m_s	Phase number of the stator
NEMA	National Electrical Manufactures Association

NI	National Instrument
N_p	Number of poles
N_r	Number of rotor bars
n_r	Rotor speed (rpm)
N_s	Number of stator slots
n_s	Synchronous speed (rpm)
n_{sp}	Slip speed
n_{bb}	Number of broken bars
p	Number of pole-pairs
PC	Personal Computer
PMSG	Permanent Magnetic Synchronous Generator
RF	Radio frequency
RMS	Root Mean Square
s	Slip
SVAF	Space Vector Angular Fluctuation
UMP	Unbalance Magnetic Pull
V	Rated voltage
VI	Virtual Instrument
α_{skew}	Skew angle
σ	Conductivity of conductor material
Φ	Magnetic Flux (Wb)
φ	Power factor angle
WT	Wavelet Transform

Diagnosis Kerosakan dan Pengawasan Keadaan untuk Motor Aruhan Tiga-Fasa Sangkar Tupai Berdasarkan kaedah Analisa Penamparan Arus Motor

ABSTRAK

Kajian tak simetri pemutar dalam motor aruhan sangkar tupai tiga fasa secara tradisinya memberi tumpuan kepada analisis kesan patah batang-batang pemutar pada medan magnet dan arus spektrum. Kebanyakan pengeluar motor telah melaporkan kes-kes kerosakan batang-batang pemutar berlaku secara rawak di sekeliling pemutar motor besar. Motor-motor yang dipantau melalui program penyelenggaraan yang berdasarkan analisis tandatangan arus motor (MCSA), dan darjah degradasi yang ditemui pada pemutar adalah lebih besar daripada yang diramalkan oleh analisis arus spektra. Satu kajian yang lengkap terdiri daripada analisis teori, serta simulasi dan ujian telah dijalankan untuk menyiasat kesan daripada bilangan dan lokasi batang-batang pemutar patah terhadap langkah-langkah diagnosis MCSA tradisional. Kaedah yang dicadangkan adalah umum untuk menganggar amplitud jalur sisi dalam kes-kes batang-batang pemutar patah berganda dan disahkan menerusi simulasi dengan menggunakan model berasaskan unsur terhingga serta ujian makmal.

Perisian LabView2010 telah digunakan untuk mendiagnosis kerosakan batang-batang pemutar yang patah dalam motor aruhan dengan pemantauan dalam talian secara langsung dalam kajian ini. Dua algoritma dicadangkan untuk menjejaki dan mengesan kerosakan batang-batang pemutar yang patah pada motor aruhan dalam keadaan muatan penuh dan muatan ringan, iaitu algoritma Transformasi Fourier Pantas (TFP) dan algoritma analisis pelbagai resolusi berasaskan Transformasi Gelombang Kecil (TGK). Keputusan yang diperoleh daripada uji kaji

ini menunjukkan bahawa TFP adalah lebih bergantung pada keadaan muatan motor aruhan. Teknik TGK menerusi sistem perolehan data LabView menunjukkan keupayaan untuk mengesan bilangan dan lokasi bar-bar pemutar yang patah dalam keadaan muatan ringan. Keputusan ini menunjukkan bahawa magnitud komponen frekuensi meningkat apabila bilangan bar yang rosak bertambah dan tertumpu pada satu kutub. Kaedah MCSA yang menggabungkan teknik TFP dan TGK boleh digunakan dengan memuaskan dan berjaya untuk mengesan bar-bar pemutar yang rosak dalam motor aruhan sangkar tupai tiga fasa. Teknik penguraian gelombang kecil ini dianggap lebih baik untuk isyarat tidak pegun. Teknik APAM memberikan tumpuan kepada analisis spektrum arus pemegun dan telah berjaya digunakan untuk mengesan bar-bar pemutar yang rosak.

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ABSTRACT

Studies of rotor asymmetries in three-phase squirrel cage induction motors have traditionally focused on analyses of the effects of the broken rotor bars on the magnetic field and current spectrum. Major motor manufactures have reported cases where damage bars are randomly distributed around the rotor perimeter of large motors. The motors were being monitored under maintenance programs based on motor current signature analysis (MCSA) in some of these cases, and the degree of degradation found in the rotor was much greater than that predicted by analysis of their current spectra. A complete study was carried out for this reason, comprising a theoretical analysis, as well as simulation and test, to investigate the influence that the number and location of broken bars has on the traditional MCSA diagnosis procedure. The proposed methodology is generalized for the estimation of the sideband amplitude in the case of multiple bars broken and validated by simulation using a finite-element based model as well as by laboratory test.

In this research, LabView2010 technique is used to diagnose the broken rotor bars faults in induction motor with direct online monitoring. Two algorithms are proposed to track and detect the broken rotor bars faults in induction motors under full load and light load conditions, namely Fast Fourier Transform (FFT) algorithm and Wavelet Transform (WT) based multi resolution analysis algorithm. The results obtained from the experiments show that FFT is significantly dependent on the loading condition of induction motor. From the experiments result, Wavelet Transform technique (WT) by LabView data acquisition system shows a capability of

detecting the number and location of broken rotor bars under light load condition. The results show that the magnitude of the sideband frequency component increases when the number of broken bars is increased and concentrated over one pole. Therefore, the MCSA method which employs both the FFT technique and Wavelet Transform can be satisfactorily and successfully applied to detect broken rotor bars fault in a three-phase squirrel-cage induction motor.

CHAPTER 1

General Overview

1.1 Introduction

Electric motors have revolutionized the standards of human lives and resulted in our present modern life style. In every product that is used, or consumed in any service facility that is avails, the contribution of an electric motor is quite obvious. To some extent, induction motors have dominated in the field of electromechanical energy conversion by having 80% of the motors in use (Benbouzid & Kliman, 2003; Wan & Hong, 2001).

Nowadays most of the motors used in industry and our modern life are squirrel cage induction motors because of their simple design, easy operation and maintenance and relatively high efficiency, as well as induction motors are also used in critical applications such as nuclear plants, aerospace and military applications, where the reliability and availability must be of high standards. For these reasons, condition monitoring and diagnostic faults are becoming more and more important issues in the field of electrical machine protection, because they can greatly improve the reliability and availability in a wide range of applications. Induction motor faults could be detected at early stage in order to prevent complete failures, reduce repair cost, excessive downtime and unexpected production costs.

With appropriate mechanical enclosures induction motors can often operate in hostile environments such as corrosive, hazardous and dusty places. They are also exposed to a variety of undesirable conditions and situations such as faulty operations. These unwanted conditions can cause the induction motor to go into a failure period, which may result in an unserviceable condition of the motor. The failure of induction motors, if not detected at its early stages of the failure period, can result in a total loss of the machine itself, in addition to a likely costly downtime of the whole plant. More important, these failures may even result in the loss of lives, which cannot be tolerated. With a well-designed motor condition monitoring system, plant operators can prevent economic losses, increase the productivity. Thus, condition monitoring techniques for early detection of the incipient motor faults are of great concern in industry and are gaining increasing attention (Chow, Tipsuwan, & Hung, 2000).

Induction motors play an important part in the field of electromechanical energy conversion. However, the broken rotor bar fault in the motor occurs frequently. Rotor failures are caused by inadequate casting and fabrication procedure or a combination of various stresses which act on the rotor, such as electromagnetic, thermal, environmental, and mechanical. Broken rotor bars faults yield asymmetrical operation of induction motors causing torque pulsation, increased losses, poor starting performance and higher thermal stress. Hence, early detection of broken bars would help to avoid catastrophic failures and reduce repair cost.

In the past two decades, there have been continuing efforts at studying and diagnosing faults in induction motors. To study the influence of the broken rotor bar fault on the motor's performance characteristics, as well as in terms of the variations of the electricity after broken rotor bar fault is an important technical method to prevent accidents appearing in the operating process and to safeguard safety in production. Analysis of induction motors with broken rotor bar fault is mainly based on electromagnetic analysis and some experts have obtained many useful research results (Mohammed, Abed, & Ganu, 2006; Faiz & Ebrahimi, 2008). Some researchers have worked on methods to detect the presence of broken rotor bars by using a search coil mounted on the motor frame for an analysis of the induced voltage waveform (Elkasabgy, Eastham, & Dawson, 1992). In some approaches (Mirafzal & Demerdash, 2005; Li, Xie, Shen, & Luo, 2007), the stator current waveforms, the magnetic force distribution on the rotor bars, the distribution of magnetic field, the iron core loss distributions on rotor tooth adjacent to broken bars can be computed based on the finite element technique and more information may be retrieved for diagnostic purpose. The use of line current as a parameter which can form the basis of a noninvasive condition monitoring system for the early detection of rotor faults in three phase induction motors is well established, and intensive research effort has been focused on the motor current signature analysis in order to detect electrical and mechanical fault condition of induction motors (Ning, 2002). Rotor bar fault detection has been implemented by monitoring the motor current signature (Costa, Almeida, Naidu, & Braga 2004) and (Benbouzid & Kliman, 2003), pulsations in speed, air gap flux and vibration (Singh & Kazzaz, 2003). Additionally the sensitivity of fault detection mainly depends on the inertia of the load and it is difficult to determine the degree of fault level. From the available literatures, the temperature-rise problem of electrical motors has aroused more and more experts' interests. Lopez-Fdez & Donsion, (1999) simulated the heating problem of a motor when one of rotor bars is totally broken. Antal & Zawilak (2005) investigated the heating characteristics of motor with non-damaged rotor and another with broken rotor bars and heat distribution in rotor. Thus, the methodologies to enhance the performance of feature extraction techniques and lessen the computational cost in their implementation form one of the most important phases of developing such a monitoring system.

The most widely used induction motor in the industry is a motor which works at the limits of its mechanical and physical properties. A good diagnosis system is mandatory in order to ensure proper behaviour in operation. The history of fault diagnosis and protection is as outdated as the induction motors themselves.

Initially, manufacturers and users of electrical machines used to rely on simple protection against, for instance, over current, over voltage and earth faults to ensure safe and reliable operation of the motor. However as the tasks performed by these motors became more complex, improvements were also sought in the field of fault diagnosis. It has now become essential to diagnose faults at their very inception, as unscheduled motor downtime can upset deadlines and cause significant financial losses.

Motor current signature analysis (MCSA) is one of the most widely used techniques for fault detection analysis in induction machines. It is based on the Fast Fourier Transform (FFT), which is currently considered as the standard. Other signal processing techniques for non-stationary signals becomes, therefore, essential. Time-frequency transforms such as wavelet analysis (Ukil & Rastko, 2006) have been successfully used with electrical systems in order to evaluate faults during transient states. The detection of induction motor faults using the wavelet transform has also been introduced especially in the case of noise or vibration signals. Interesting approaches have been presented recently (Calis & Cakir, 2007) and (Bacha, Gossa, & Capolino, 2008) which introduce the analysis and monitoring of fluctuations of motor current zero-crossing instants and the use of artificial intelligence solutions such as neural networks. A recent publication (Niu, Son, Yang, Hwang, & Kang, 2008) presents an interesting approach of discrete wavelet transform applied to the evaluation of different statistic feature extraction techniques.

LabVIEW is a powerful graphical programming development for data acquisition and control, data analysis and data presentation. It is ideal for creating virtual instruments. LabVIEW features a well-defined strategy for constructing both hardware and software modules that are easy to understand and maintain (Elliott, Vijayakumar, Zink, & Hansen, 2007). The virtual instruments can be rapidly combined, interchanged, and shared to build custom applications. Different hardware acquisition options can feature drop in replacement virtual instruments for truly modular application development.

Therefore, the signal processing techniques are used in present work for detection of common faults of induction motor. Signal processing techniques have their limitations. For example, the reliability of detecting the rotor fault using Fast Fourier Transform FFT depends on loading conditions and severity of fault. If the loading condition is too low or the fault is not too severe, Fast Fourier Transform may fail to identify the fault. Therefore, different techniques such as Wavelet Transform (WT) are investigated in the research work to find better features for detecting common faults under different loading conditions.

This work starts with a description of the theoretical approach of MCSA bases and signal processing techniques proposed, followed by a presentation of experimental results. The use of the wavelet transform improves fault detection, and to implement an online monitoring system. The MCSA (Motor Current Signature Analysis) techniques have been investigated as the feature extraction methods for broken rotor bar detection in 3-phase squirrel-cage induction motors having 1000W, 4 poles, and 415 V, 1400 rpm, 1.5A and 50 Hz ratings.

1.2 Motivation for This Research Work

In this research work, condition monitoring and fault detection of induction motors are based on the signal processing techniques. The signal processing techniques have advantages that these are not computationally expensive and these are simple to implement. Therefore, fault detection based on the signal processing techniques is suitable for an automated on-line condition monitoring system. Signal processing techniques usually analyse and compare the magnitude of the fault frequency components, where the magnitude tends to increase as the severity of the fault increases. Therefore, the aim of this thesis is to utilize the signal processing techniques for detection of broken rotor bars faults of induction motor. In the present research work, LabVIEW environment is used to diagnose the faults with direct online monitoring. LabVIEW software may be a better option for direct interfacing with the system.

This research focused on the monitoring and analysis of the rotor fault diagnosis of a 3-phase squirrel-cage induction motor based on motor current signatures analysis for both cases in healthy condition or when the motor has broken rotor bars. In order to perform accurate and reliable analysis on induction motors, the installation of the motors and measurement of their signal need to be reliable. Therefore, the first aim of this thesis is to design an experimental procedure and an experimental set up that can accurately monitor the signals and can introduce a particular fault factor to the motor in isolation of other faults. Stator current contains unique fault frequency components that can be used for detection of various faults of motor.

1.3 Research Objectives

This research is focused on the condition monitoring and fault diagnosis of broken rotor bars in 3-phase squirrel-cage induction motor. The main objectives can be outlined as follows:

a) To develop the FFT and Discrete Approximation Wavelet Transform (DAWT) technique by used LabVIEW to diagnose the broken rotor bars faults with direct online monitoring.
b) To investigate the effectiveness of DAWT in predicting broken rotor bars faults in induction motor using Labview data acquisition system.
c) To investigate the influence of locations of broken rotor bars on the magnitude of sideband harmonics using Labview data acquisition system.
d) To compare the results obtained from both FFT method and DAWT technique for better option in predicting broken bars fault in induction motors.
e) The research investigates the applications of advanced signal processing techniques to detect broken rotor bars faults.
f) To model and simulate the performance and characteristics of induction motors having broken rotor bars in FEM.

1.4 Scope of the Work

The reliability of condition monitoring and fault diagnosis depends upon the best understanding of electrical and mechanical characteristics of the motors in the healthy state and faulty condition. Stator current contains unique fault frequency components that can be used for detection of various faults of induction motor.

In this research work, condition monitoring and fault detection of induction motors is based on the signal processing techniques. The signal processing techniques have advantages that these are not computationally expensive and these are simple to implement. Therefore, fault detection based on the signal processing techniques is suitable for an automated on-line condition monitoring system. Signal processing techniques usually analyze and compare the magnitude of the fault frequency components, where the magnitude tends to increase as the severity of the fault increase.

Figure 1.1 shows the various steps involved in the framework, using the stator current signals in healthy and faulty conditions. The framework consist of two way the first is by using finite element method for simulation and modeling three-phase squirrel cage induction motor in order to analyze and understand the electric, magnetic and mechanical behavior in induction motor during healthy and faulty state. The second way is by using real induction motor for testing in healthy and faulty state with on-line monitoring stator current signal with help of wavelet transform analysis and FTT. The key point is to diagnose the faults by monitoring the parameters of motor operations such as stator current waveform and spectrum frequency.

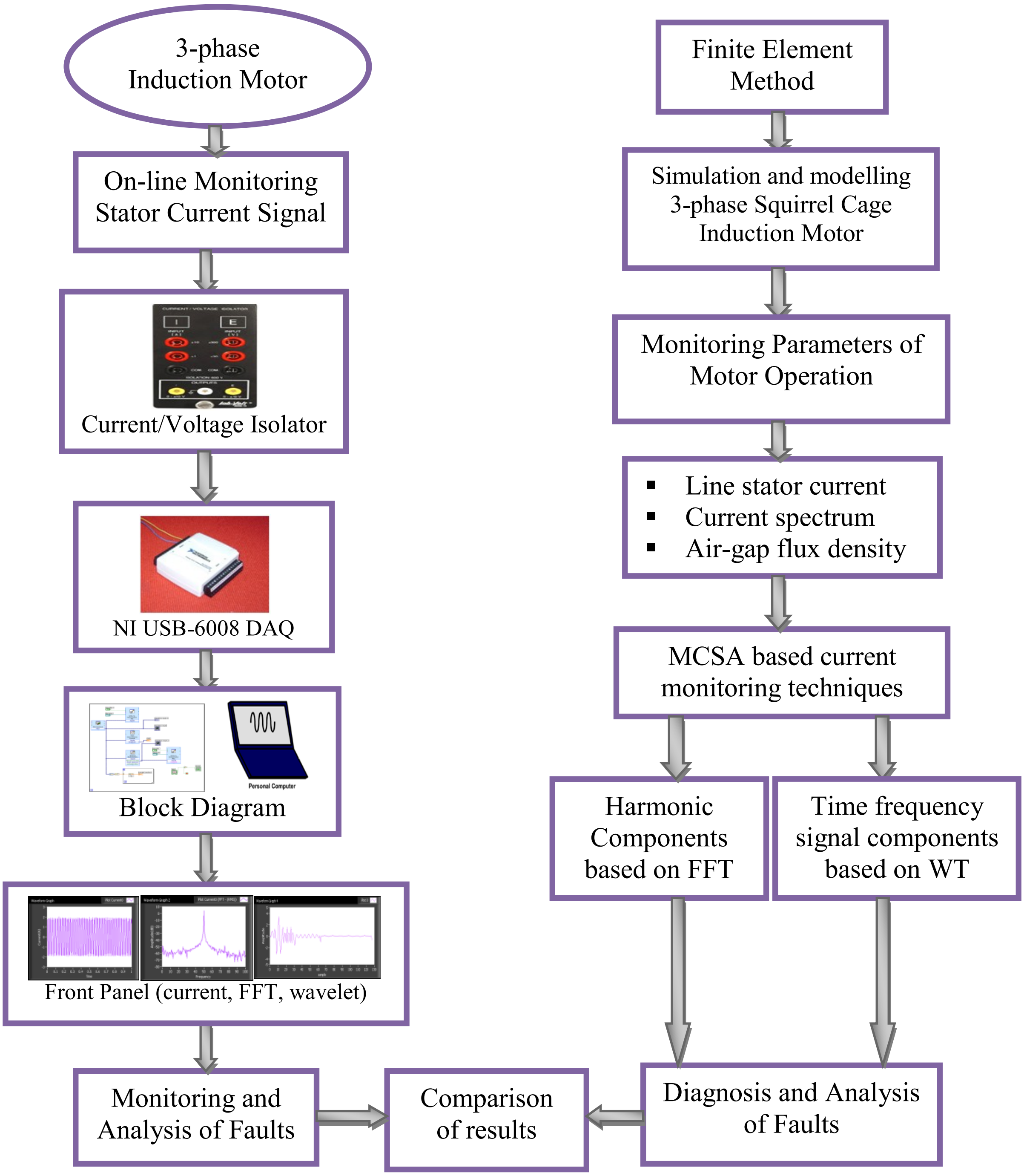

Figure 1.1 Framework for the induction motor fault monitoring method

1.5 Contribution of Thesis

The main aim of the research work is to diagnose broken rotor bars faults experimentally with the help of suitable signal processing techniques. In order to perform accurate and reliable fault monitoring and capture analysis on induction motors, an experimental set up is designed that can accurately measure the current signals and can then introduce a decision making process to determine the fault in the induction motor. In the present research work, Labview environment is used to diagnose the faults with direct online condition monitoring. The contributions of this research are summarized as follows:

a) Has systematically demonstrated that the magnitude of sideband harmonics can vary with both total number of broken rotor bars and also the precise location of broken bars in the rotor structure.

b) Has successfully implemented the FFT method and DAWT signal processing method in Labview data acquisition system for monitoring broken rotor bars faults in induction motors.

c) Has successfully demonstrated that DAWT has better capability detecting faults based on different location of broken rotor bars.

1.6 Thesis Outlines

This thesis comprises of five chapters including this one. In the interest of brevity, this work presents the results in a staggered manner, as explained below. As a necessary background, motivation, research objectives, scope of the work and contribution of thesis are described in chapter one.

In chapter two, background knowledge of broken rotor bar in induction motor and their diagnosis is reviewed. This chapter starts with a description of the theoretical approach of MCSA bases and a signal processing technique proposed, also discusses the MCSA techniques as feature extraction methods for broken rotor bar detection, and investigates processing techniques that lead to improvement in feature extraction performance and easiness in the implementation.

In chapter three, broken rotor bar fault dynamics will be illustrated using the squirrel-cage induction motor mathematical equation. The characteristic signatures to detect broken rotor bar fault are elaborated. The present work discusses the fundamentals of MCSA plus condition monitoring of the induction motor using MCSA. The simulation results by FEM opera-2d show that MCSA can effectively detect abnormal operating conditions in induction motor applications.

Chapter four discusses the experimental work for diagnosis of broken rotor bar faults in induction motors operating under different load conditions is presented. Experiments are performed using MCSA based fault detection techniques such as Fast Fourier Transform and Wavelet Transform. To diagnose the fault with these techniques, a laboratory test bench was set up. It consists of a three-phase squirrel cage induction motor coupled with permanent magnetic synchronous generator (PMSG). The rated data of the tested three-phase squirrel cage induction machine were: 1000W, 415 V, 50 Hz and 4 poles. The speed of the motor was measured by digital tachometer. The Virtual Instrument (VIs) was built up with programming in LabVIEW2010. This VIs was used both for controlling the test measurements and data acquisition, and for data processing. The NI-6008DAQ was used to acquire the current samples from the motor under different load conditions. The experiment shows that MCSA can effectively detect broken rotor bars and other high resistance faults.

Chapter five presents the conclusion and scope for future work. The research investigates the applications of advanced signal processing techniques to detect broken rotor bars faults. The research work helps in understanding the applications and limitations of fault detecting techniques. It is observed that LabVIEW is user friendly software and is very helpful in detecting the faults on line. The new detecting methods proposed in this work are able to diagnose motor’s faults more sensitively and more reliably.

CHAPTER 2

Literature Review

2.1 Introduction

Induction motors are the prime movers of industry and permeate all areas of the modern life. Generally, they are robust and reliable. The motor faults are due to mechanical and electrical stresses. However, due to the combination of poor working environments, heavy duty cycles, and installation and manufacturing factors, internal faults often occur on the rotor, stator, bearing and accessory parts of induction motors. The most common faults that induction motors are afflicted with include broken rotor bars, stator winding faults and air gap eccentricity. Over the past decade, these issues have produced a number of studies on the diagnosis of broken rotor bars in induction motors. In these investigations, several techniques, such as electromagnetic field air-gap and spectrum frequency of stator current monitoring, temperature measurements, and rotor speed measurements, vibration monitoring and non-invasive MCSA, for diagnosis of broken rotor bars have been proposed. One of the main reasons for using MCSA monitoring techniques is because of the fact that the other techniques require more invasive access to the motor. This implies that the operation of the motor may have to be interrupted in order to install the necessary equipment for any reliable signal to be sensed. Thus, the MCSA monitoring technique, which is completely noninvasive and does not interrupt the operations of the drive systems, is often favored. However, in recent years, MCSA monitoring techniques have received much attention.

2.2 General Overview

In this chapter, the concepts of induction motor condition monitoring and broken rotor bars fault diagnosis from previous research are introduced as a literature review. Significant efforts have been dedicated to induction motor fault diagnosis during the last two decades and many techniques have been proposed (Mirafzal & Demerdash, 2005) and (Cristaldi, Lazzaroni, Monti, Ponci, & Zocchi, 2004). Thus, a brief description of the main techniques presented in the literature, as well as their advantages and disadvantages are presented in this section.

Several fault detection and identification techniques are based on stator current spectral signature analysis, which uses the power spectrum of the stator current to detect broken rotor bars faults. These fault detection techniques are based on the magnitude of certain frequency components of the stator currents. Specifically, a Fast Fourier Transform (FFT) of the current is taken. The first spectral peak less than the fundamental frequency are called the low sideband. The magnitude of the low sideband is measured and compared to a threshold. The result of this comparison determines if an induction motor has broken rotor bars. However, these techniques may fail to detect induction motor fault conditions because the sidebands can be masked due to the windowing processes used to compute the power spectrum of the current signals, as was shown in (Mirafzal & Demerdash, 2006).

The detection of induction motor faults under steady-state and transient operating conditions have been improved by several studies. In these studies, features, such as increase of vibration, decrease of mean torque, increase of losses, decrease of efficiency, frequency spectrum of the magnetic flux density and torque were used to diagnose the fault as in (Thomson & Barbour, 1998; Arkan, Kostic-Perovic, & Unsworth, 2005).

Other techniques include vibration analysis, acoustic noise measurement, torque profile analysis, temperature analysis, and magnetic field analysis (Siddique, Yadava, & Singh, 2005). These techniques require sophisticated and expensive sensors, additional electrical and mechanical installations, and frequent maintenance. Moreover, the use of a physical sensor in a motor fault identification system results in lower system reliability compared to other fault identification systems that do not require extra instrumentation. This is due to the susceptibility of the sensor to fail added to the inherent susceptibility of the induction motor to fail.

Other techniques based on artificial intelligence AI approaches have been introduced, using concepts such as fuzzy logic (Wan & Hong, 2001), genetic algorithms (Siddique et al., 2005), and Bayesian classifiers (Povinelli, Johnson, Lindgren, & Ye, 2004). The AI based techniques can not only classify the faults, but also identify the fault severity. These methods build offline signatures for each motor operating condition and an online signature for the status of a motor being monitored. A classifier compares the previously learned signatures with the signature generated online in order to classify the motor operating condition and identify the fault severity. However, most of these AI based techniques require large datasets. These dataset are used to learn a signature for each motor operating condition that is being considered for classification. Thus, a large amount of data is needed to train such algorithms in order to cover the most common motor operating conditions, and obtain good motor fault classification accuracy. Moreover, AI based techniques for motor fault classification may not be sufficiently robust to classify faults from different motors from those used in the training process. Additionally, these datasets are usually not available; involve destructive testing, and considerable time to generate.

Additionally, a method using the motor internal physical condition based on a so-called pendulous oscillation of the rotor magnetic field space vector orientation has been introduced for motor fault classification (Mirafzal & Demerdash, 2005). This technique classifies the faults and identifies the fault severity of induction motors with broken rotor bars or short winding. However, this index identification based technique needs to evaluate each new motor to obtain the correct set of indexes in order to correctly classify the faults.

Overlooking this fact will deteriorate the performance of the detection. The result of this study showed 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. Finally, it was suggested that the proposed method is a mathematically general and powerful one which can be utilized to detect any fault that could show up in the motor current.

Acosta, Verucchi, & Gelso, (2006) presented a new method for detecting broken rotor bar faults by analyzing the stator induced voltage after removing the mains. The method is attractive because source non-idealities like unbalance time harmonics will not influence the detection. Also it is clear from the nature of the test that it can be performed even with an unloaded motor. Harmonic components predicted by theoretical analysis are clearly matched by simulation results. However, due to inherent asymmetries of the motor, some of these components may already exist, even in a healthy motor. It is also apparent from the simulations and experiments that, although the number of broken bars does not have much effect on the magnitude of the harmonic components, one can distinguish between a faulty and a healthy machine. Inter bar currents, dependence of the spectral amplitude on the instance of disconnection, and short length of data also adversely affect on the detection technique. Benbouzid & Kliman, (2003) investigated the efficacy of current spectral analysis on induction motor fault detection. The frequency signatures of some asymmetrical motor faults, including air gap eccentricity, broken bars, shaft speed oscillation, rotor asymmetry, and bearing failure, were identified. This work verified the feasibility of current spectral analysis.

Benbouzid, Nejjari, Beguenane, & Vieira, (1999) stated that 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 utilizes the results of spectral analysis of the stator current. Reliable interpretation of the spectra is difficult, since distortions of the stator current waveform caused by the abnormalities in the drive system are usually minute. Their investigations show that the frequency signature of some asymmetrical motor faults can be well identified using the FFT, leading to a better interpretation of the motor current spectra. Laboratory experiments indicate that the FFT based motor current signature analysis is a reliable tool for induction motor asymmetrical faults detection. Bentounsi & Nicolas, (1998) discussed an adaptive time frequency method to detect broken bar. 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.

Currently, broken rotor bars, short turn winding failures, static and dynamic eccentricity, are detected by analyzing the frequency spectrum of the induction motor current as in (Nandi, Bharadwaj, & Tolivat, 2002). Reliable detection of the broken rotor bars requires the correct identification of the harmonic components in the current coming from mechanical disturbances of the rotor in (Thomson & Fenger, 2001). The analysis of a faulty induction motor by the time-stepping finite element method obviated all problems and drawbacks of analytical and traditional lumped-parameter modeling methods as in (Faiz, Ebrahimi, & Sharifian, 2007). FE coupled state space has been used to predict the characteristic frequency components that are indicative of rotor bar and connector broken in the stator current waveform, respectively as in (Bangura & Demerdash, 1999). In the modeling of rotor broken bars by (Elkasbagy et al., 1992) and (Fiser, 2001), the currents of the broken bars were taken as zero. Inter-bar currents reduced the magnetic flux density asymmetry by broken bars as in (Walliser & Landy, 1994). This makes detection of broken bars more difficult, particularly at early stages. In Kia, Henao, & Capolino, 2007), stator current asymmetry was employed for diagnosis of the broken rotor bar fault. It was shown by (Schoen & Habetler, 1995), that the level of load and occurrence of fault influences the stator current spectrum; if the stator current is visualized in the synchronous reference, an existing magnetic asymmetry influences both d and q components of the current, while the load fluctuation affects only the q component. Sideband components around the current fundamental harmonic have been suggested for detecting broken-bar fault by (Fiser, 2001; Kliman, Koegl, Stein, & Endicott, 1988). In (Nandi, Bharadwaj, Tolivat, & Parlos, 1999), spectrum analysis of the stator current was used to detect and recognize the number of broken rotor bars. In (Bellini, Filippetti, Franceschini, Tassoni, Passaglia, Saot-tini, Tontini, Giovannini, Rossi, 2000), the spectrum of the field current component in a field-oriented controlled motor was used for fault diagnosis. In (Elkasbagy et al., 1992), the amplitude of the bar current and total rotor current were used for determination of broken rotor bars. In (Haji & Toliyat, 2001), a pattern recognition technique based on Bays minimum error classifier was developed to detect broken rotor bar faults in induction motors at the steady state. Lyubomir & Chobanov, (2004) conducted an experiment to diagnose the broken rotor bar fault. MCSA was used to diagnose the fault of motor. For this, experiment was conducted on 0.5kw induction motor. The spectra of health and faulty motor were compared. Stator current spectrum of faulty motor shows the side bands at particular frequencies due to presence of broken rotor bars with great reliability. Finally, researchers concluded that MCSA is a reliable technique for diagnosis of broken rotor bar faults.

In (Kothari & Nagrath, (2005), a model-based fault diagnosis system was developed for induction motors using a recurrent dynamic neural network for transient response prediction and multi resolution current processing for non stationary signal feature extraction. In (Bellini, Filippetti, Franceschini, Tassoni, Passaglia, Tontini, Giovannini, Rossi, 2002), the sum of the side band components around the supply frequency produced by electric asymmetry was used as the diagnostic index. In (Zhu & Wu, 2005), detection method of faulty rotor bars based on wavelet ridge was presented. In (Benbouzid & Kliman, 2003), the spectrum of the stator current using Park's vector approach was used to detect broken rotor bars in faulty motors. In (Calıs & Cakır, 2007), a fluctuation of stator current at zero crossing times (ZCT), which is independent of the motor parameters, was used to diagnose the broken bar. In (Angrisani, Daponte, & Apuzzo, 1996), wavelet packet decomposition of the stator current was used for the on-line noninvasive detection of broken rotor bars. In (Mirafzal & Demerdash, 2005), the pendulous oscillation of the rotor magnetic field orientation was implemented as a fault signature for rotor fault diagnostic purposes at a steady-state operation. In (Ondel, Boutleux, & Clerc, 2006), features extracted from the current and voltage measurement were used to build up a pattern recognition vector to detect broken bars. In (Mirafzal & Demerdash, 2006), a swing-angle indicator that is based on the rotating magnetic field pendulous oscillation concept was used for diagnosis of the broken rotor bar fault. In (Mohamad et al., 2006), a discrete wavelet transform (DWT) was used to extract different harmonic components of the stator current for broken bar fault diagnosis. In (Douglas & Pillay, 2005), it was shown that using high order wavelets improve the ability to detect broken rotor bars in induction motors operating under transient conditions. In (Ye, Sadeghian, & Wu, 2006), a wavelet packet neuro-fuzzy inference was used to set the feature coefficients of mechanical faults extracted from the stator current.

Mehrjou, Mariun, Hamiruce-Marhaban, & Mistron, (2011) intended to review and summarize the recent researches and developments performed in condition monitoring of the induction motor with the purpose of rotor faults detection. The bar breakage is the major fault in the rotor of squirrel-cage induction motor. Once a bar breaks, the condition of the neighboring bars also deteriorates progressively due to the increased stresses. This causes high thermal and mechanical stresses; pulsating mechanical loads, such as reciprocating compressors or coal crushers, can subject the rotor cage to high mechanical stresses. The reliability of the condition monitoring techniques depends upon the best understanding of the electrical and mechanical characteristics of the machines in the healthy and faulty condition. All condition monitoring addressed are on-line monitoring technique except induced voltage, motor circuit analysis and surge test.

Szabó Bíró, & Dobai, (2003) utilized the result of spectral analysis of stator current to diagnose rotor faults. The diagnosis procedure was performed by using virtual instrumentation (VIs). Several virtual instruments (VIs) were built up in Labview. These VIs were used both for controlling the test measurements and data acquisition and for the data processing. The tests were carried out for seven different loads with healthy motor, and with similar motors having up to 5 broken rotor bars. The measured current signals were processed using the FFT. The power density of the measured phase current was plotted. The results obtained for the healthy motor and those having rotor faults were compared, especially looking for the sidebands components having the special frequencies.

The significance presence of some well defined sidebands frequencies in the harmonic spectrum of the measured line current clearly indicated the rotor faults of the induction motor.

Jung, Lee, & Kwon, (2008) proposed an online induction motor diagnosis system using MCSA with advanced signal and data processing algorithms. The diagnosis system was composed of the DSP board for high speed signal processing and advanced signal and data processing algorithm including the PC user interface. The advanced algorithms were made up of the optimal slip estimation algorithm, the proper sample selection algorithm, and the frequency auto search algorithm for achieving MCSA efficiently. The optimal slip estimation algorithm suggested the optimal slip estimator based on the Bayesian method of estimation. In addition, the proper sample selection algorithm determined the standard of suitable samples for the MCSA process from the characteristics of a measurement noise and spread spectrum.

Finally, the frequency auto search algorithm detected the abnormal harmonic frequency under unspecified harmonic numbers with the tendency of the candidate spectrum magnitudes. To verify the generality of the suggested algorithms, laboratory experiments were performed with 3.7kW and 30kW squirrel-cage induction motors. The proposed system was able to ascertain four kinds of motor faults and diagnose the fault status of an induction motor. Experimental results successfully verified the operations of the proposed diagnosis system and algorithms.

Szabó, Toth, Kovacs, & Fekete, (2008) compared different fault diagnosis methods by means of data processing in LabVIEW. The results obtained by experiments verified that the three-phase current vector, the instantaneous torque, and the outer magnetic field can be used for diagnosing the rotor faults. At last, authors stated that due to its simplicity of MCSA, this method is the mostly used in industrial environment.

Chidong & Guang, (2009) developed a multi taper based detection method for incipient motor faults in order to detect weak fault eigen frequency submerged in noises environment. The tradeoff problem between frequency resolution and variance was studied, and the optimal tradeoff value was chosen to be applied on detecting motor faults. By selecting high energy tapers, the root leakage of eigen frequency was eliminated, and the shape of eigen frequency was changed to be distinguishable. Simulation studies were conducted and results show that multitaper method has a steadier and anti noise performance compared with other methods. Finally, an experiment was arranged in laboratory, and the bearing faults were put into the motor. By using the proposed method, it is validated that multitaper method is effective for detecting the motor incipient faults.

In this chapter, the literature on condition monitoring of 3-phase induction motor is reviewed. This review covers some important topics such as condition monitoring, fault diagnosis, electric monitoring, motor current signature analysis, Fast Fourier Transform, Wavelet Transform, signal processing techniques. In addition, this review also covers the major developments in this field from early research to most recent.

2.3 Faults in 3-Phase Squirrel-Cage Induction Motor

Squirrel-cage induction motor faults can be categorized into electrical and mechanical faults. Electrical faults asymmetries can be also categorized into rotor and stator faults. All these possible faults in induction motors and their associated subsets are summarized as depicted in the block diagram schematic of Figure 2.1.

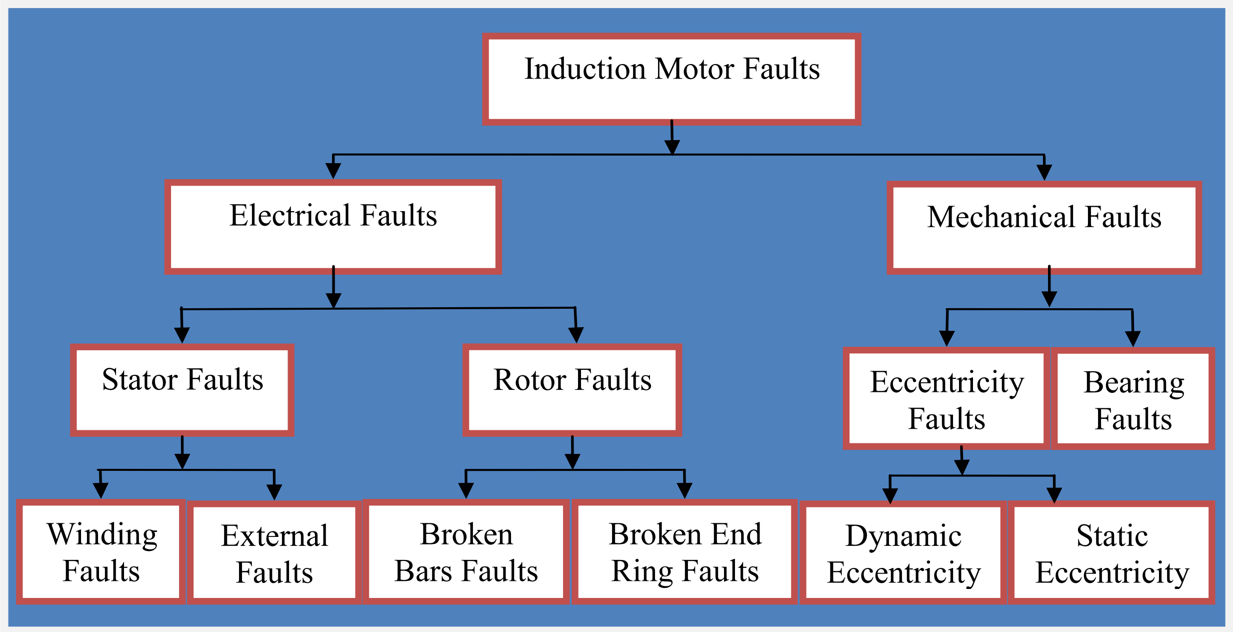

Figure 2.1 Block diagram of induction motor faults categories

The major faults of electrical machines can broadly be classified as the following (Ratna & Mehala, 2007):

i. Abnormal connection of the stator windings.
ii. Broken rotor bars or racked rotor end ring
iii. Static and/or dynamic air gap irregularities.
iv. Bent shaft (akin to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings.
v. Shorted rotor field winding.
vi. Bearing and gearbox failures.

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

i. Unbalanced air gap voltages and line currents.
ii. Asymmetrical distribution flux density in the air gap.
iii. Increased torque pulsations.
iv. Decreased average torque.
v. Increased losses and reduction in efficiency.
vi. Excessive heating.

In recent years, intensive research in (Cardoso, Cruz, Carvalho, & Saraiva, 1995; Lebaroud & BentounsI, 2003) effort has been focused on the technique of monitoring and diagnosis of electrical machines and can be summarized as follows;

i. Time and frequency domain analysis.
ii. Time domain analysis of the electromagnetic torque and flux phasor.
iii. Temperature measurement, infrared recognition, radio frequency (RF) emission monitoring.
iv. Motor current signature analysis (MCSA).

- Model, artificial intelligence and neural network ANN based techniques
- LabVIEW DAQ techniques to process the current profiles.
- Electromagnetic field monitoring using search coils, or coils wound around motor shafts (axial flux related detection)
- Induction motor current signature analysis based on wavelet packet decomposition (WPD) of the stator current
- Broken rotor bars, discrete wavelet transform(DWT)

v. Detection by space vector angular fluctuation (SVAF).

vi. Noise and vibration monitoring.

vii. Acoustic noise measurements.

viii. Harmonic analysis of motor torque and speed.

2.4 Faults in Rotor

The faults mentioned above are potential hazards to the reliability and safety of operation, and also increase the operational costs. The broken rotor bar is a common type of fault in induction motor. Although it does not cause motor failure initially, broken rotor bar faults significantly lower the efficiency and shorten the life of an induction motor. Damages to insulation and winding structure may be caused consequently resulting in motor breakdown eventually. Arcing and sparking caused when induction motors operating with broken rotor bars can be dangerous if motors are situated in mining or petroleum environments where flammable gasses are present**.** Typical cage rotor construction of an induction motor is shown in Figure 2.2.