UNIVERSITI PUTRA MALAYSIA

MIXED ECCENTRICITY FAULT DETECTION BASED ON STATOR CURRENT ANALYSIS IN LINE START PERMANENT MAGNET SYNCHRONOUS MOTOR

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By

MAHDI KARAMI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2015

DEDICATIONS

To my soul mate and love of my life,
the one who is my everything,

Dr. Saba Sabaghi

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

MIXED ECCENTRICITY FAULT DETECTION BASED ON STATOR CURRENT ANALYSIS IN LINE START PERMANENT MAGNET SYNCHRONOUS MOTOR

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May 2015

Chairman: **Norman Mariun, PhD**
Faculty: **Engineering**

A detection strategy for three-phase, 4-pole LSPMSM under mixed eccentricity fault through motor current signature analysis (MCSA) is proposed in this investigation. An experimental test rig is provided to integrate different steps of designed methodology in order to sample the stator current signal of case study motor at the given rates under several operation conditions. Low degree of mixed eccentricity with 17% static and 17% dynamic eccentricity is developed to identify the efficient fault-related components at specific frequencies with the capability of fault detection at early stages. Mixed eccentricity degrees are increased with 33% dynamic and 17% static eccentricity as well as 33% static and 17% dynamic eccentricity where it is also provided to evaluate the effects of static and dynamic eccentricity on the harmonic components pertaining to mixed eccentricity. Effect of mechanical load on mixed eccentricity fault detection in LSPMSM is investigated via change the load levels from 0% to 100% within six steps in the condition monitoring process. A simulation study based on finite element method (FEM) is carried out using the real parameters and practical conditions such as motor design parameters, mixed eccentricity degrees and load levels in order to derive the efficient results for eccentricity detection process. Current spectrum of case study motor under 17% static and 17% dynamic eccentricity is investigated and it is indicated that the amplitudes of fault-related components at rotor frequency 25 Hz increased by 18% in experimental results and 13.2% in the numerical evaluation which are the highest incremental rate in comparison with the components of third and fifth harmonics of rotor frequency i.e. 75 Hz and 125 Hz. Further increase of dynamic eccentricity degree by 33% at fixed static eccentricity degree of 17% leads to raise the amplitudes of mixed eccentricity-related harmonic components at 25 Hz, 75 Hz and 125 Hz by 26.6%, 12.7% and 5.4% respectively. While the degree of static eccentricity is increased to 33% at fixed degree of dynamic eccentricity 17%, the incremental variation in the amplitudes of harmonic components at 25 Hz, 75 Hz and 125 Hz is 15.5%, 12.7% and 1.8%, respectively. It is derived that mixed eccentricity fault generates harmonic components at 25 Hz, 75 Hz and 125 Hz in the stator current of LSPMSM while the amplitudes of these harmonic components increase proportional to fault severity. Furthermore, the effect of dynamic

eccentricity on the aforementioned harmonic components is superior to static eccentricity. Increase the level of mechanical load in LSPMSM result in reduces the amplitudes of harmonic components related to mixed eccentricity while these amplitudes increase upon the progress of fault degree for fixed load. Accordingly, mixed eccentricity fault in LSPMSM is scrutable only in the fixed levels of load.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MENGENALPASTI KEROSAKAN KEEKSENTRIKAN CAMPURAN BERDASARKAN ANALISIS ARUS PEMEGUN PADA MOTOR SEGERAK MAGNET KEKAL MULA SEBARIS

Oleh

MAHDI KARAMI

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Strategi pengesanan keeksentrikan campuran untuk LSPMSM tiga-fasa, 4-kutub dengan menggunakan analisis tanda arus motor (MCSA) telah dicadangkan dalam penyiasatan ini. Ujian rig dilaksanakan untuk mengintegrasikan langkah-langkah yang berbeza daripada kaedah yang telah direka bertujuan untuk mengambil bacaan isyarat arus pemegun motor kajian kes pada kadar yang ditetapkan di bawah beberapa keadaan operasi. Keeksentrikan campuran tahap rendah dengan 17% statik dan 17% dinamik dibangunkan untuk mengenal pasti kerosakan yang berkaitan pada frekuensi tertentu dengan keupayaan mengesan kerosakan di peringkat awal dengan cekap. Darjah keeksentrikan campuran ditingkatkan dengan 33% dinamik dan 17% statik dan juga 33% statik dan 17% dinamik di mana ia juga dijalankan untuk menilai kesan keeksentrikan statik dan dinamik pada komponen harmonik yang membawa kepada keeksentrikan campuran. Kesan beban mekanikal ketika pengesanan keeksentrikan campuran pada LSPMSM juga disiasat dengan mengubah tahap beban 0% hingga 100% dalam enam langkah ketika proses pemantauan keadaan. Satu kajian simulasi berdasarkan kaedah unsur terhingga (FEM) dilakukan dengan menggunakan parameter sebenar dan syarat praktikal seperti parameter reka bentuk motor, darjah keekstrikan campuran dan tahap beban untuk mendapatkan hasil terbaik bagi proses pengesanan keeksentrikan. Spektrum arus motor pada 17% keeksentrikan statik dan 17% keeksentrikan dinamik disiasat dan ia menunjukkan amplitud komponen kerosakan pada frekuensi pemutar 25 Hz dalam keputusan eksperimen meningkat sebanyak 18% dan 13.2% dalam penilaian berangka yang merupakan kadar tertinggi peningkatan berbanding dengan komponen harmonik ketiga dan kelima frekuensi pemutar iaitu 75 Hz dan 125 Hz. Peningkatan selanjutnya pada keeksentrikan dinamik sebanyak 33% dengan keeksentrikan statik masih kekal sebanyak 17% membawa kepada peningkatan amplitud komponen harmonik yang berkaitan dengan keeksentrikan campuran masing-masing pada 25 Hz, 75 Hz dan 125 Hz sebanyak 26.6%, 12.7% dan 5.4%. Walaupun tahap keeksentrikan statik dinaikkan kepada 33% dengan tahap keeksentrikan dinamik kekal pada 17%, perubahan tambahan amplitud komponen harmonik pada 25 Hz, 75 Hz dan 125 Hz masing-masing adalah 15.5%, 12.7% dan 1.8%. Ianya diketahui keeksentrikan campuran menjana komponen harmonik dalam arus pemegun

LSPMSM pada 25 Hz, 75 Hz dan 125 Hz manakala amplitud komponen harmonik meningkat berkadaran dengan tahap kerosakan. Tambahan pula, kesan keeksentrikan dinamik pada komponen harmonik yang dinyatakan di atas adalah melebihi keeksentrikan statik. Meningkatkan tahap beban mekanikal pada LSPMSM mengurangkan amplitud komponen harmonik yang berkaitan dengan keeksentrikan campuran manakala amplitud ini meningkat ketika tahap kerosakan pada beban tetap. Oleh itu, keeksentrikan campuran pada LSPMSM dapat diperhatikan hanya pada tahap beban yang tetap.

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I certify that a Thesis Examination Committee has met on 25 May 2015 to conduct the final examination of Mahdi Karami on his thesis entitled "Mixed Eccentricity Fault Detection based on Stator Current Analysis in Line Start Permanent Magnet Synchronous Motor" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctoral in Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFPM	Axial Flux Permanent Magnet
AC	Alternating Current
DC	Direct Current
emf	Electromotive Force
FEM	Finite Element Method
FOS	Fast Orthogonal Search
FFT	Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IM	Induction Motor
LSPMSM	Line Start Permanent Magnet Synchronous Motor
MCSA	Motor Current Signature Analysis
mmf	Magnetomotive Force
MUSIC	Multiple Signal Classification
MPB	Magnetic Powder Brake
N.m	Newton Meter
NEMA	National Electrical Manufacturers Association
ORNL	Oak Ridge National Laboratory
PMSM	Permanent Magnet Synchronous Motor
PSD	Power Spectral Density
pdf	Probability Density Function
RMS	Root Mean Square
RSM	Reluctance Synchronous Motor
SRM	Switched Reluctance Motor
UMP	Unbalanced Magnetic Pull
WFM	Winding Functions Method

A	z-component of the Magnetic Vector Potential
α	Transfer Angle of Mixed Eccentricity
B	Magnetic Flux Density or Magnetic Induction
C_s	Stator Symmetrical Axis
C_r	Rotor Symmetrical Axis
C_g	Rotor Rotation Axis
D_m	Mixed Eccentricity Degree
D_s	Static Eccentricity Degree
D_d	Dynamic Eccentricity Degree
F_s	Sampling Frequency
$f_{Nyquist}$	Nyquist Frequency or Folding Frequency
f_{max}	Maximum Frequency
Δf	Frequency Resolution
f_{rotor}	Rotor Frequency
f	Supply Frequency
g_0	Uniform Air-Gap Length
i	Stator Phase Current
J	Current Density
J_o	Applied Current Density Due to the Supply
J_e	Current Density Due to Time Variation of Magnetic Flux

J_v	Current Density Due to Motional Induced Voltage
k	Odd Integer Values
l	Motor Length in z-direction
L_p	Inductance
N	Number of Samples
p	Number of Pole Pair
p_r	Number of Poles
R_p	Phase Resistance
t	Time
T_s	Time Step
T	Sampling Period (acquisition time)
ν	Reluctivity
V_p	Input Voltage Source
υ	Conductor Speed Against B
V_i	Induced Voltage per Phase
μ	Permeability
$x(t)$	Continuous Signal
$x(n)$	Discrete Signal
σ	Electrical Conductivity

CHAPTER 1
INTRODUCTION

In this chapter, a description of the problems, aim and objectives and scopes of this dissertation is presented. A short background about the extent of this research work is discussed and the contribution to the knowledge is specified. This chapter ends with the layout of thesis.

1.1 Background

Improving the electric motors efficiency is crucial and one of the most effective measures to reduce primary energy consumption, which cause global warming [1]. The efficiency improvement of induction motors (IMs) among all types of electric motors is the most effective action since the vast number of IMs currently installed in industry that consume immense portion of total energy used by electric motors [2]. Recent developments in permanent magnet technology facilitate the utilization of high efficiency permanent magnet synchronous motors (PMSMs) as an alternative for IMs. However, the inverter-fed characteristic of PMSMs makes them uneconomical for single speed applications [1].

A hybrid (IM/PMSM) electric motor known as line start permanent magnet synchronous motors (LSPMSM) has been introduced to gain both high efficiency and starting capability without inverter [3]. The LSPMSM is well-suited to new standards that receive more attention in the academic and industrial sectors because it represents a good alternative to replace the IM [1], [3]. The stator of LSPMSM is similar to that of IM while its rotor contains a combination of cage and permanent magnets [4]. The LSPMSMs have remarkable running properties in addition to acceptable starting capability [5].

While an electric motor is operating in various applications, the electrical and mechanical parts of motor influence by some stresses of forces and conditions which lead to different failures [6]. The prevalent defects in electrical motor are due to mechanical faults and represent up to 50%–60% of the faults [7]. Statistics reveals that nearly 80% of the mechanical faults are due to eccentricity of stator and rotor in IMs [8] that emphasize the importance of eccentricity fault among the critical and severe faults in electrical motors.

Rotor symmetry axis, stator symmetry axis and rotor rotation axis coincide in a normal electrical motor. Eccentricity means the separation of these axes from their origin [9]. This displacement is the reason for categorizing eccentricity fault in three types, so-called static eccentricity, dynamic eccentricity and mixed eccentricity [10]. It is very important to note that eccentricity fault always emerges in the form of mixed eccentricity, and pure static or dynamic eccentricity does not occur in practice

[11]–[16]. Eccentricity fault causes asymmetry of air gap magnetic flux, voltage and current; increasing losses and reducing the efficiency; enhancing the torque and speed fluctuations; diminishing the average torque; increasing temperature [9].

Eccentricity fault gradually damages the electric motor while in a severe case leads to rub between the rotor and stator and damages the stator winding and the rotor cage [17]. For this reason, an important issue regarding eccentricity fault is detection at its early stages to avoid accidental and unpredictable shutdown of motor due to the progress of faults that lead to financial loss that cannot be recuperated.

An effective condition monitoring system that can manifest the condition of electric motor in order to detect the eccentricity is a key requirement of maintenance. This system should be able to detect any changes in the motor quantities to predict the necessity of maintenance before major breakdown occurs. A variety of condition monitoring techniques is reported for detecting different faults in electrical motors involving various domains of science and technology [18]–[20].

Some of the techniques in this aspect can be mentioned as electromagnetic field monitoring, instantaneous power monitoring, temperature measurement, infrared recognition, radio-frequency emissions monitoring, vibration monitoring, chemical analysis, acoustic emissions and motor current monitoring [18]. It is noticeable that, motor current signature analysis (MCSA) is a well-known and effective technique among the existing monitoring methods [21].

The raw signal obtained from condition monitoring strategy should be processed using a signal processing technique in order to extract the relevant features that are sensitive to the specific fault. Several techniques have been introduced for harmonic analysis where the selection of such methods depends on the nature of the signal and required information.

1.2 Problem Statement

Due to natural aging phenomenon and other factors in practical applications, LSPMSM is subjected to different faults. Those faults disturb the safe operation of motor, threaten normal manufacturing, and result in substantial cost penalties. Mixed eccentricity among the high possibility and critical faults can produce a type of fault cycle [7], [8], [22] in LSPMSM and consequently lead to reducing the performance and permanent failure. Despite the growth in productivity of LSPMSM for various applications, an accurate eccentricity fault feature for detection of mixed eccentricity is a key requirement of maintenance since no research work is reported in this case. The proposed mixed eccentricity detection scheme based on the cost-effective and efficient monitoring technique known as MCSA is expected to be precise enough for three-phase LSPMSM.

1.3 Objectives

In terms of knowledge creation, the project involves research into detection of mixed eccentricity fault in three-phase, 4-pole LSPMSM. In order to achieve this, the research work is divided into the following specific research objectives:

1. To fabricate the relevant segments in order to implement different degrees of mixed eccentricity fault in three-phase, 4-pole LSPMSM model TA80-4.

2. To sample the stator current signal of case study motor under steady state operation for both healthy and faulty conditions.

3. To simulate a three-phase, 4-pole LSPMSM with different degrees of mixed eccentricity according to practical design parameters of case study motor using finite element method in order to obtain the stator current signal for both healthy and faulty conditions.

4. To represent the current signals in frequency domain using power spectral density technique in order to identify the mixed eccentricity-related features.

1.4 Scope of Study

In this research, focus is given to introduce a feature for detection of mixed eccentricity fault in three-phase, 4-pole LSPMSM during the steady state operation condition. Accordingly, the effect of mixed eccentricity in case study motor is investigated. The accuracy of research outcomes are examined through a professional laboratory examination in addition to a simulation performance. The influence of load level on mixed eccentricity-related harmonic components are scrutinized and data acquisition has been carried out while the tested LSPMSM running at 0%, 20%, 40%, 60%, 80%, 100% of its rated load.

The effect of mixed eccentricity fault severity in LSPMSM is evaluated for fault-related harmonic components in this research. Different degrees of mixed eccentricity are implemented in case study motor based on the proposed method using the fabricated segments instead of normal parts. The limitations of motor structure and available industrial equipment allow the mixed eccentricity degree to be changed as the combinations of 17% static - 17% dynamic eccentricity, 17% static -33% dynamic eccentricity and 33% static – 17% dynamic eccentricity.

Three-phase, 4-pole LSPMSM is simulated in 2-D environment on the basis of finite element method (FEM) using Maxwell 2-D software. The specification of simulated LSPMSM exactly matches with the motor that is used in the laboratory test. Three-phase sinusoidal voltages are applied to the motor terminals as windings excitation. The transient solver with time integration method based on backward Euler is employed to obtain the steady state current of LSPMSM. Same percentages of mixed eccentricity fault and load levels as that of implemented in the laboratory

examination are applied in the simulated LSPMSM. The simulated and measured stator current signals are processed by power spectral density (PSD) technique for feature extraction.

The area of current research is limited to objectives mentioned above in order to investigate the effect of mixed eccentricity type of fault in three-phase, 4-pole LSPMSM. Accordingly, investigation on other types of faults, application of further condition monitoring methods and other signal processing techniques are beyond the objectives of this thesis.

1.5 Contribution of the Thesis

1. None of the previous researches attempt for eccentricity fault detection in LSPMSM due to the different constraints such as availability of motor and complexity of the fault. Since the LSPMSM is newly launched and its application growing gradually, this research work tries to investigate the effects of mixed eccentricity in this type of motor via simulation and experimental examinations which is one of the major contributions of this dissertation.

2. The remarkable features are proposed for mixed eccentricity fault detection in three-phase 4-pole LSPMSM based on MCSA due to accessibility, cost-effective and noninvasive characteristics of stator current monitoring.

3. Lastly, this work could pave the way for further research in different faults and detection techniques for LSPMSMs.

1.6 Thesis Layout

The thesis consists of five chapters in which each chapter presents the flow of the research study involved. This thesis is devoted to the detection of mixed eccentricity fault in LSPMSM through stator current monitoring. The outline of the thesis is as follows:

Chapter One gives a brief introduction of the research background of this study. The research requirements are stated as the problem statement to define the key research aspects used. The objective and aim of the study are listed to set the focus of the research. Subsequently, the scope of research work and relevant contributions are highlighted.

Chapter Two presents the background of research work in terms of the eccentricity fault in different types of electrical motors. The necessity and general structure of LSPMSM technology are described. Different condition monitoring and signal processing methods for fault detection in electrical motors are comprehensively documented. The chapter ends with research trends in eccentricity fault detection for various types of electrical motors.

Chapter Three presents the methodology that includes the experimental setup; the laboratory test process and the measurement setup used in this research work; the proposed method for mixed eccentricity implementation in case study motor; experimental procedure; the FEM to simulate the demonstrated machine in order to compute the stator current signal and the PSD for signal processing and feature extraction are explained towards end of the chapter.

Chapter Four presents the results and discussions on the effect of mixed eccentricity fault in case study motor. The eccentricity-related harmonic components are discussed based on the power spectral density measurement of the reference signals. Variation in the amplitudes of fault-related harmonic components due to fault severity is described. The motor loading effect on mixed eccentricity-related features is scrutinized.

Chapter Five concludes the thesis dissertation in terms of the proposed features for mixed eccentricity detection in three-phase, 4-pole LSPMSM. Also, this chapter includes a few suggestions that can be implemented in this research field in the future.

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