Electrical machine fault analysis and modelling by using electromagnetic approach

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**NANYANG
TECHNOLOGICAL
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**ELECTRICAL MACHINE FAULT ANALYSIS AND
MODELLING BY USING ELECTROMAGNETIC
APPROACH**

ZHANG MENGQI

**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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LIST OF ABBREVIATIONS

EV	Electric Vehicle
MEA	More Electric Airplane
PM	Permanent Magnet
FEM	Finite Element Method
MEC	Magnetic Equivalent Circuit
UMP	Unbalanced Magnetic Pull
MMF	Magneto-Motive Force
SmCo	Samarium-Cobalt
NdFeB	Neodymium-Iron-Boron
MCSA	Machine Current Signature Analysis
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
CT	Current Transformer
RTD	Resistive Thermal Detector
DTS	Distributed Temperature Sensing
PD	Partial Discharge
AI	Artificial Intelligence
ANN	Artificial Neural Networks
CAD	Computer Aid Design
KVL	Kirchhoff's Voltage Law
KCL	Kirchhoff's Current Law
EMF	Electromotive Force

PWM	Pulse Width Modulation
IM	Induction Machine
Hz	Hertz
EM	Electromagnetic
SE	Static Eccentricity
DE	Dynamic Eccentricity
ME	Mixed Eccentricity
SC	Search Coil
RPM	Revolution per minute

LIST OF SYMBOLS

B	Magnetic flux density
H	Magnetic flux intensity
B_r	Remanence
H_c	Coercivity
P	Permeance
R	Reluctance
μ	Permeability
μ_0	Permeability of free space and air
μ_r	Relative permeability
f	Frequency
p	Number of pole pairs
e	Electromotive force
Φ	Magnetic flux
F	Magnetomotive force
J	Current density
G	Conductance
E	Electric field intensity
σ	Conductivity
A	Magnetic potential
∇	Divergence operator
$\nabla \times$	Curl operator
$[Y]$	Sparse matrix Y

λ	Flux linkage
θ	Initial angle for abc-to-dq transformation
λ_{PM}	Rotor magnetization flux linkage
L	Inductance
l	Length
l_g	Airgap length
h	Height
W	Width
M	Mutual inductance
ϕ	Back yoke magnetic flux
T_e	Electrical torque
N	Number of turns

ABSTRACT

Although electrical machines have been used in a wide range of industrial applications for many decades, the demand for machine reliability in the present day is higher than ever before and it is growing continuously. Currently, due to increasing motivation to enhance machine operation reliability, the area of machine fault analysis has attracted considerable attention. This thesis introduces a less reported approach by using electromagnetic characteristics for machine fault analysis and modelling. The technical contents can be briefly abstracted into four aspects.

Firstly, a generalized approach to design magnetic equivalent circuit model for the interior permanent magnet machine is proposed. The numerical modelling by finite element method is popular in predicting machine operating performance, due to its high degree of accuracy. However, its long computation time, especially when the machine is connected to external circuit, makes it less promising in repeatedly assessing the machine performance. Here, another numerical modeling technique based on the magnetic equivalent circuit method is used to develop machine model. Compared to the finite element method, this model gives consistent prediction of machine flux distribution and exhibits faster computational speed.

Secondly, a lumped MEC model has been proposed to predict machine performance incorporating rotor motion. This lumped model has also been used to investigate the influence of partial inter-turn winding short-circuit fault. Machine operating characteristics such as flux linkage, inductance, and electromagnetic torque have been evaluated in good agreement with finite element analysis under both healthy and

faulty conditions. This investigation broadens the applications of magnetic equivalent circuit method which was mainly used for machine design optimization purpose in the previously reported studies.

Thirdly, a simplified method to assess machine irreversible demagnetization risk caused by stator inter-turn winding short-circuit fault is proposed. It has been reported in the previous researches that the stator phase short-circuit is the main cause of machine irreversible demagnetization fault. The study in this thesis indicates that the stator inter-turn winding short-circuit fault can also result in irreversible demagnetization for the bar-wound permanent magnet machines. Moreover, an analytical model is designed to predict winding short-circuit current, which significantly reduce the time required by finite element method to assess machine irreversible demagnetization.

Finally, a dual search coil method is proposed to detect machine airgap eccentricity condition. Machine flux distribution is not symmetric in the presence of airgap eccentricity, and the situation can be reflected as variations of search coil terminal voltage induced by machine magnetic field. In this study, the time-stepping FEM analysis is used to model machine static-, dynamic-, and mixed- airgap eccentricity fault conditions. The dual search coils are placed at both airgap main magnetic field and stray magnetic field to detect machine operating abnormality due to eccentric airgap. The results show that airgap eccentricity can be recognized by comparing the fundamental voltage component of search coils. This configuration is suitable for the eccentricity fault detection of low-cost machines.

CHAPTER 1 INTRODUCTION

1.1 Motivation

The rising concerns in environmental problems stimulate the desire to develop more environmental-friendly and energy-efficient products. Good examples to represent these state-of-the-art products are the development of wind turbine, electric vehicle (EV), and more-electric-aircraft (MEA), which play an important role in reducing emissions of greenhouse gases and environmental pollutants. In the meantime, electrical generators/motors technology is becoming more and more important because they are the key components in the power generation and transmission systems in these green industries.

Even though electrical machines have been applied to a wide range of industrial applications several decades ago, the requirements from transportation and renewable energy industry for machine reliability in the present day is higher than ever before and keep growing. Benefiting from the development of power electronics and magnetic material, progresses have been gained in the aspects of machine controllability, power conversion efficiency, and operation reliability. However, machine fault is unavoidable, and the hostile operation condition in the transportation industry and offshore environment makes machine fault even more likely to occur. Consequently, the faulty machine may fail in service and results in production losses,

or even result in catastrophic system failure that risk passengers' life in the case of transportation applications.

In order to minimize the impact to electrical machines, the research on fault related to analysis, modelling, and condition monitoring have attracted great attention in the past decades. New techniques and methods have been continuously brought in this research area for the purpose of achieving comprehensive understanding and early detection of various types of machine fault. More importantly, these research works not only aims to detect the electrical machine fault, but also serves as a guideline for electrical machine control and design, which eventually as a whole, improves machine operation reliability and extends its useful life.

There are plenty of works which can be observed so far, focusing on modelling and analyzing machine faults. Generally, these methods may be summarized as: machine equivalent model based method, machine operation output signal processing based method, and experimental and emerging technology based method [1, 2]. Nonetheless, the continuous development is also supported by the fact that there is no specific approach considered as the best and which provides a general solution for machine fault modelling, detection, and analysis, because the research objective should always adapt to the specific machine operating condition and its application. In this regard, machine load characteristics, fundamental fault causes, potential failure modes, and other relative machine operation conditions should be included when conducting machine fault analysis [3, 4].

As a result, there are many problems and challenges remaining to be investigated for electrical machine fault analysis. Particularly, in considering different machine types, scale and size, operation and load conditions, instrument availability, etc. It also provides many opportunities for engineers and researchers who work on this area, to find out new techniques to further improve the reliability of electrical machines for the present day.

1.2 Objectives

As introduced in last section, plenty of research works have been done in the electrical machine fault related area, but so far the developed technologies are rarely applied. This is supported by the fact that most electrical machines are operating without any condition monitoring or fault detection technologies. In practice, the advanced technologies usually require many extra devices, resulting in additive cost which is too expensive for the terminal users [3]. Here, we notice all the machine faults will result in abnormal variation in the electromagnetic field, which is a good angle for machine fault modelling and analysis.

The main purpose of this study is to discover the potentials of using electromagnetic characteristics for machine fault analysis, i.e. to improve machine fault-tolerant capability, to achieve early fault detection. This work is strongly supported by our project sponsor Vestas, and the detailed objectives are:

Objective 1 – Developing a fast and convenient numerical tool to quickly and accurately evaluate magnetic flux distribution and investigate the impacts arising from machine faults.

Machine performance can be accurately evaluated according to the flux-current relations obtained by numerical modeling. Nowadays, the numerical tools based on finite element method (FEM) has achieved huge success, such as Ansoft Maxwell and JMAG Designer, which are extensively used for the analysis and design of industrial applications. However, the FEM is slow in computation, and the commercialized tools cannot meet all demands of different research focuses. Hence, it is necessary to develop a more flexible and convenient tool to ease the evaluation of machine flux distribution and operation characteristics.

Objective 2 – Investigating the characteristics of irreversible demagnetization caused by stator winding short-circuit fault and proposing design guidelines to avoid demagnetization fault.

Machine fault analysis shall eventually serve the final target that to improve machine operation reliability and fault-tolerant capability. For bar-wounded permanent magnet (PM) machine, stator winding short-circuit could not only cause machine phase imbalance, but also induce strong magnetic flux that may irreversibly demagnetize the magnets. Hence, it is important to characterize machine flux under short-circuit condition and assess the risk to cause demagnetization fault, to make sure the demagnetization fault will not happen when operating the machine under winding short-circuit fault tolerant mode.

Objective 3 – Solving the difficulty in detecting airgap eccentricity fault by using magnetic flux as fault indicator.

Machine operation condition monitoring alone can be an independent subject. During studying machine fault, we realize the market available solutions to detect machine eccentricity fault are expensive, while using electromagnetic field may give a better choice since it is very sensitive to detect eccentric airgap. Therefore, we prefer to consider eccentricity fault analysis together with fault detection in the research, because machine abnormal operation condition is essentially the early symptom of machine fault. Our purpose is to find a cost-effective approach to identify machine airgap eccentricity.

1.3 Contributions

The main contributions of this work can be summarized as below:

1. A numerical model based on magnetic equivalent circuit (MEC) method is proposed to predict the flux distribution and operating characteristics of PM machines. The model design takes into account magnetic saturation effect and magnetic cross-coupling due to rotor saliency. This novel model is designed in a more generalized way which can adapt to different machine structures and rotor positions. Compared to the FEM analysis, the numerical model is much faster in computation speed and delivers appealing accuracy for both healthy and stator short-circuit operation condition. This work extends the functionality of MEC model and the results also prove the usefulness of MEC model to work as a fast computational tool for electrical machine fault analysis.

2. Previous-reported studies [5, 6] have shown that stator phase short-circuit can cause irreversible demagnetization fault at some critical machine operation conditions. They are used as a guideline or reference to improve the machine design and fault mitigation techniques. The study in this thesis proves that not only phase short-circuit, but the inter-turn winding short-circuit fault can also result in irreversible demagnetization fault in bar-wounded PM machines. This phenomenon is replicated by means of transient FEM analysis. Furthermore, an analytical model is developed to predict the short-circuit current which significantly reduce the time required by FEM analysis. Overall, the presented work demonstrates a quick risk assessment of demagnetization fault under inter-turn winding short-circuit, which fills the gap of investigation irreversible demagnetization for bar-wounded PM machines.

3. A method to detect machine airgap eccentricity is proposed, based on the idea that magnetic flux distribution is symmetric between machine poles. It relies on simple coil sensors to gauge the variation in both airgap main flux and leakage stray flux due to machine airgap eccentricity. Our study shows that airgap main flux is a good indicator to detect eccentricity fault, while the stray flux less sensitive but gives more flexibility and non-invasive to the machine.

1.4 Organizations of the thesis

This thesis contains seven chapters with thorough introductions, analyses, and conclusions from the studies in electrical machine fault. A brief introduction of each chapter is given below:

Chapter 1 gives a brief introduction on the research motivation as the kick-off of this study. Subsequently, the objectives, contributions, and the organizations of this thesis are presented.

Chapter 2 reviews the major types of electrical machine faults, the development of electrical machine fault analysis, and the techniques for electrical machine fault detection and protection. The merits and drawbacks of these techniques are discussed and the representative publications are introduced.

Chapter 3 presents the design procedure of the numerical MEC model for an interior PM machine. This machine has V-type magnet configuration and bar-wound stator winding. The model design follows the principle of using minimum number of flux tubes to capture machine magnetic flux distribution. Model computation speed and accuracy is gauged by comparison with FEM analysis.

Chapter 4 presents a lumped MEC model which is able to investigate the influence of stator winding short-circuit fault. The magnetic circuit for moving airgap is extensively designed to deal with the flux path change due to rotor motion. Machine operation parameters for both healthy and faulty conditions are compared.

Chapter 5 proposes an approach to assess the risk of irreversible demagnetization for a machine under inter-turn winding short-circuit fault. An analytical model is developed to predict short-circuit. Critical machine operation conditions which will result in demagnetization fault are found by means of FEM analysis.

Chapter 6 introduces a method to detect airgap eccentricity fault. Static-, dynamic-, and mixed-eccentricity conditions of a squirrel cage induction machine and PM machine are created by using FEM. Dual coil sensors are used to gauge the variation of magnetic field due to eccentric airgap.

Chapter 7 concludes the studies included in this thesis and presents the recommendations for future research work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The history of electrical machine fault analysis is almost as archaic as the machine itself. In general, fault may occur in any of the machine structural components such as stator, rotor, bearing, as well as the power converter connected to it. Some of the machine faults are due to unavoidable fatigue or aging of the machine components. Maintenance must be scheduled according to the useful life of aging components to keep the machine operating in healthy condition. However, the remaining useful life of aging components is difficult to determine, where a conservative estimation may guarantee machine's health but unnecessarily increase the maintenance cost. Given these factors, the early detection of abnormal machine operating is expected, so the aging components can be replaced before their maximum useful life.

Machine fault also can be caused by improper operating condition such as overloading [2]. Usually, the duration of this kind of incidence is short, and fault is likely to be mitigated if machine is tolerant to the sudden change. Therefore, there are two aspects which need to be considered in order to improve machine reliability, whereby improving machine fault-tolerant capability when fault occurs, and mitigating the fault to reduce the duration of faulty operation [3]. In this regard, improving machine operation reliability requires comprehensive studies in the research areas include machine operation condition monitoring and fault detection,

fault-tolerant machine design, faulty machine performance prediction, machine control and fault mitigation, etc.

Figure 2-1 Types of electrical machine fault

Electrical machine fault can occur in all of its components, due to the underlying causes which include defective component, poor installation, inadequate maintenance, improper operation, or a combination of these [3]. As shown in Figure 2-1, the major types of machine faults can be broadly classified, according to the related part and influence, into winding fault, mechanical fault, and magnetic fault [7]. Among them, airgap eccentricity is usually a consequence of mechanical fault, demagnetization fault only occurs in PM or hybrid PM machines, machine core problem is categorized into magnetic fault because lamination is magnetic conducting material.

Broken rotor bar fault is specific to squirrel-cage induction machine. According to [8], this fault accounts for about 10% of induction machine faults, where the main cause is the high resistive cage bar due to cracking. When current pass through the crack, it creates unexpected heat and rise the localized temperature, which can melt down the insulation material. The short-circuit on the cage bar can induce unbalanced rotor magnetic force and airgap eccentricity at early stage [9]. There is no effective method reported in the literature to directly detect broken rotor bar when machine is operating. Instead, machine airgap eccentricity may be found, but the difficulty is to differentiate it from the other potential causes of airgap eccentricity, such as shaft bend and bearing fault [10].

The symptom of rotor winding short-circuit is similar to broken rotor bar fault, which usually happens in operating slip ring induction machine, doubly fed induction machine, and conventional synchronous generator. The fault can be detected by investigating the current signature if the rotor winding is connected with current sensor [11]. Otherwise, the airgap eccentricity will be detected instead, but again, it will be difficult to find the exact fault cause without stopping the machine for off-line maintenance.

The majority of electrical machines use rolling element bearing. This type of bearing consists of a set of balls placed in raceways between its inner and outer rings. It has been reported that about 40%-50% of machine failure is related to bearing fault, which is caused by improper lubrication and installation, corrosion, or mechanical fatigue. However, few articles can be found that is dedicated in investigating bearing

problems. Instead, the bearing fault is usually manifested as airgap asymmetry and they are covered in the category under the airgap eccentricity fault [7].

Machine core fault is usually found in large scale electrical machines such as hydro power generators. It is usually caused by the broken insulation between core laminations and the localized hotspot due to the eddy current. When the temperature keep increasing, it can burn or melt the laminations and eventually cause machine shutdown [12]. Although this type fault is not commonly seen, the repair requires the entire replacement of stator core and re-winding the coil, which results in significant amount of financial losses. The conventional method to detect core fault is by using full ring test which requires a low power factor source in MVA level, such high power rating brings critical safety issue and also the machine has to be stopped from operation [13].

In this chapter, the review of published studies will focus on stator winding short-circuit fault, irreversible demagnetization fault, and airgap eccentricity fault. The modelling techniques, faulty machine performance prediction, and protection against fault will be mainly discussed.

2.2 Stator winding short-circuit fault and machine performance evaluation

2.2.1 Introduction of stator winding short-circuit fault

Stator winding short-circuit fault occupies a large portion of about 21% of all electrical machine fault [14]. It usually starts from broken insulation with inter-turn

winding short-circuit, due to ageing and degradation caused by temperature stress, moisture, mechanical stress or inverter-fed ripple [15]. The fault will induce over-rated current flow in the winding and bring the over-heating problem. If the inter-turn fault deteriorate further, more and more winding turns may be shorted and result in partial winding short-circuit (short-circuit between coils) fault, or even worse, result in phase-to-phase or phase-to-ground short-circuit fault. Hence, the general designation of stator winding short-circuit fault can be divided into the following types:

- inter-turn winding short-circuit (same phase)
- partial winding short-circuit (same phase)
- phase-to-phase short-circuit fault (two or more phases)
- phase-to-ground short-circuit

The protection against machine stator winding short-circuit fault can be categorized into: early detection of inter-turn winding short-circuit fault; and condition monitoring of the stator insulation. In early 1980s, the negative-sequence component of stator phase current is firstly used as fault signature to detect machine inter-turn winding short-circuit [16]. Since then, other transforms of stator current are also found to detect this fault, such as current's park vector [17], current's extended park vector [18], envelop of the stator current [19], stator current in multiple reference frame [20], and the wavelet transform [21, 22]. These techniques all use the alternative view of stator current and they can be called the machine current signature analysis (MCSA) method.

Condition monitoring of stator insulation method intends to detect the degradation of winding insulation instead of detecting short-circuit directly. It could provide crucial information on the health condition of stator insulation and give warnings prior to the failure of insulation [23]. In this case, condition monitoring of stator insulation method could provide earlier protection compared to inter-turn winding short-circuit detection method. So far, various techniques have been used to monitor winding insulation, such as slot temperature monitoring by using resistive thermal detectors (RTD) [24] and distributed temperature sensing (DTS) by using a single optic fiber sensor [25]. Partial discharge detector (PD) and surge tester are commercial available devices to monitor the health of winding insulation, where the PD test can be conducted either on-line or off-line, while surge test can only be taken off-line [26]. Both PD and surge tests are more suitable for large size of electrical machines due to the cost reasons [27]. Last but not least, some techniques are published to estimate the lifespan of winding insulation based on its aging mechanism, such as a degradation model using stress parameters in [28] and a cable monitoring method using impedance spectrum analysis in [29]. The estimation accuracy is subjected to machine operating characteristics and material properties, whose reliability needs to be further improved for industrial applications.

Although these techniques exhibit good performance in protecting machine against fault, inter-turn winding short-circuit cannot be avoided in machine operation. Generally, electrical machine can continuous operate under inter-turn or partial winding short-circuit conditions, while the phase-to-phase or phase-to-ground short-circuit can force the machine to shut down. Therefore it is important to know the influence

of inter-turn or partial winding short-circuit fault to make sure the machine drive can tolerant the fault and keep regulating machine in a tolerant manner.

Figure 2-2 Machine phase circuit-based model to represent inter-turn winding short-circuit [30]

2.2.2 Analytical model for stator winding short-circuit fault

The knowledge of impact caused by inter-turn winding short-circuit is important to operate the machine. These information can be extensively used to regulate machine in order to avoid catastrophic failure, such as for fault mitigation control and fault-tolerant machine design purposes [31]. A commonly used method to conduct fault analysis is by using the analytical model, which is based on machine phase circuit and winding connections [30, 32].

As shown in Figure 2-2, the conventional phase diagram of a PM machine is modified by adding a fault insulation resistance r_f , and the original winding is divided into healthy and faulty parts a_{s1} and a_{s2} respectively. Subsequently, the circuit-based model can be derived as equations to evaluate machine voltage and current relations, as given by:

$$\begin{bmatrix} V_{as_1} \\ V_{as_2} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_{a1} & 0 & 0 & 0 \\ 0 & R_{a2} & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{as} - i_f \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as_1} \\ e_{as_2} \\ e_{bs} \\ e_{cs} \end{bmatrix} + \begin{bmatrix} L_{a1} & M_{a_1a_2} & M_{a_1b} & M_{a_1c} \\ M_{a_1a_2} & L_{a2} & M_{a_2b} & M_{a_2c} \\ M_{a_1b} & M_{a_2b} & L_s & M_s \\ M_{a_1c} & M_{a_2c} & M_s & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{as} \\ i_{as} - i_f \\ i_{bs} \\ i_{cs} \end{bmatrix} \quad (2.1)$$

where the R_s , L_s and M_s are the stator phase resistance, self- and mutual inductance. R_{a2} and L_{a2} are the resistance and the self-inductance of the faulty winding a_{s2} . M_{a1b} and M_{a1c} are mutual inductances between a_{s1} and the windings b_s and c_s . In addition, M_{a1a2} , M_{a2b} and M_{a2c} are respectively the mutual inductances between the a_{s2} and the windings a_{s1} , b_s and c_s .

The electromagnetic torque under inter-turn winding short-circuit fault can be predicted by:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c - e_f i_f}{\omega_m} \quad (2.2)$$

where ω_m is the machine mechanical angular speed.

The parameters in the circuit-based model can be estimated from the number of winding turns and airgap function [30, 33]. Once the parameters are determined, the circuit-model can be used to evaluate faulty machine performance and machine input/output relations. This analytical model is easy to understand as it intuitively describe the fault mechanism by introducing the short-circuit path. It is also computationally efficient which is suitable for quick faulty machine performance

evaluation. However, the circuit-based model does not always reflect the actual machine performance as it relies on the accuracy of parameters such as winding self-inductance and mutual inductance, which depends on the flux distribution during faulty condition. Furthermore, the flux-current relation under faulty machine operating condition is also determined by the machine structure, magnetic saturation, and asymmetric stator magnetization [22, 34]. Therefore, it is necessary to use more precise models which can possibly include all the faulty machine operating particularities to conduct the machine performance prediction..

2.2.3 Electrical machine analysis under short-circuit condition using FEM

The FEM is a numerical technique to solve partial differential equations of boundary governed problems, such as solid and thermal mechanics. The application of FEM to solve electromagnetic field problem is firstly proposed in 1970s [35]. With the development of processing capability of computers in the past decade, the numerical method by using FEM takes an irreplaceable role for machine design and fault analysis due to its high accuracy.

The FEM is able to take into account the magnetic saturation and cross-coupling effects due to machine material and structural characteristics, which are usually omitted or estimated by empirical factors using conventional analytical circuit-based methods. In this way, the flux distribution in different parts of machine can be obtained with high degree of accuracy. Typically, the deviation of predicted machine performance by FEM and actual machine performance is less than 10% if all machine particularities are included [36, 37].

Figure 2-3 Mesh created by finite element method for machine analysis

The fundamental principle of FEM is to divide the electrical machine into a certain number of element (mesh generation in other word) as shown in Figure 2-3. Then, the Maxwell's equation is applied to calculate the current-flux relations on the elements according to the machine structure and material magnetic property. For example, in the most popular 2-D magnetostatic analysis, the magnetic flux in the domain Ω can be calculated as:

$$W(A) = \iint_{\Omega} \left[\int_0^B H dB - JA \right] d\Omega + \int_{S_2} H_t A dS \quad (2.3)$$

$$\frac{\partial}{\partial x} \left(\frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial A}{\partial y} \right) = -\mu J \quad (2.4)$$

$$\begin{cases} A = A_{z0} \text{ on first boundary condition } S_1 \\ \frac{\partial A}{\partial n} = -\mu H_t \text{ on second boundary condition } S_2 \end{cases}$$

where A is magnetic vector potential, B is the flux density, H is the magnetic strength, J is the current density, μ is the material permeability, A_{zo} is the first boundary condition, and H_t is the tangential component of second boundary condition.

By applying the calculation to all of the elements, magnetic flux distribution in the electrical machine can be obtained upon solving the matrix:

$$[C][A] = [S] \quad (2.5)$$

where $[C]$ is the matrix containing all coefficients, $[A]$ is the matrix containing all magnetic potentials, and $[S]$ is the matrix containing all current sources.

In the presence of stator winding fault, the excitation source to compute magnetic vector potential through Maxwell's equation become a critical factor, which is not only determined by the winding connection but also the flux evaluated by FEM. In this case, the FEM modelling is required to couple with external circuit and conduct transient analysis in order to predict faulty machine performance. This function to incorporate external circuit has been implemented in several commercial FEM packages, such as Ansoft Maxwell and JMAG Designer, and the corresponding faulty machine performance prediction and parameter evaluation can be found in many publications [31, 38, 39].

Nevertheless, the simulation of short-circuit part in external circuit breakdown the symmetry of magnetic flux distribution, this changes requires FEM analysis updates the coupling of electrical circuit and magnetic circuit in the geometry and all the

meshing has to be restarted in order to be coupled with external circuit. In this way, the FEM analysis requires much longer computational time compared to magneto-static or healthy machine analysis, which is also the main disadvantage to use external circuit coupled FEM for faulty machine analysis [40]. For example, the simulation of a large-scale PM machine in 3D (approx. 2 million elements) for one periodic of electric angle using Intel Xeon E5-2670 CPU takes more than 2000 minutes as shown in [41].

Table 2-1 GPU acceleration reported by commercial available FEM package vendors for high performance computation[41, 45]

<i>Package name</i>	<i>GPU acceleration compared to CPU computation</i>
ABAQUS	2x for 1 GPU vs. 4 cores 1.7–2.4x for 2 GPU vs. 12 cores
RADIOSS	1.8–2.5x for 1 GPU vs. 4 cores 6.5–7.5x for 2 GPU/node vs. 12 cores
MSC Nastran	1.55–2x for 2 GPUs vs. 8 cores
ANSYS Mechanical	1.7–2.1x for 1 GPU vs. 8 cores
LS-DYNA	1.06–3.3x for 1 GPU vs. 8 cores
JMAG Designer	20–28x for 1 GPU vs. 1 core 6–8x for 1 GPU vs. 4 cores

Therefore, many publications are dedicated to improve the computational efficiency when dealing with transient analysis. Typically, the computational efficient finite element analysis (CE-FEA) can be achieved by simplifying FEM analysis and making it more task-specified. For example, a flux density estimator coupled FEM

analysis to find optimal machine torque is presented in [42], where the estimator is introduced to eliminate partial meshing of machine geometry, and the computational speed is more than 100 times faster than the case without estimator [43]. Similar studies have been found in [44], where the modified FEM analysis is used to evaluate machine time harmonic radiated fields, the computational time is also found to be about 100 times less than the 3D full model. However, this type of CE-FEA has certain limitations, which are only available for specific modelling objectives.

In comparison, a more generalized way to improve FEM computational efficiency is by using high performance computation (HPC), which does not reduce the total computational loads of FEM analysis but diversify the loads into multiple processors by introducing parallel computation [46]. This technique has drastically improved the computational efficiency of FEM analysis, especially for the computation using Graphic Processing Unit (GPU), which has evolved from a fixed-function special-purpose processor into a highly parallel, multithreaded, manycore processor with tremendous computation power and high memory bandwidth [47]. Table 2-1 has presented the computational speed of FEM analysis by GPU compared to conventional CPU. Although there is a significant difference between the accelerations reported by different vendors, most likely due to the numerical solver, boundary condition, or specific applications used, it can be clearly seen that GPU has improved the computational efficiency of FEM analysis by a certain order of magnitude.

However, in addition to the cost of FEM package and HPC devices, the vendors usually charge for extra expense if GPU solver is required. As a matter of fact, this

high expense is unaffordable for many researchers, and the problem of low computational efficiency still exists in using FEM analysis.

2.3 Irreversible demagnetization under short-circuit fault

2.3.1 Introduction of irreversible demagnetization fault

The PM machines are featured with high power density and wide constant power range. This benefit essentially comes from the use of permanent magnets embedded in the machine. Nowadays, the permanent magnets for electrical machine are usually made from rare-earth material, such as samarium-cobalt (SmCo) and neodymium-iron-boron (NdFeB), which are able to generate strong magnetization flux with small volume and weight [48]. On the other hand, the use of permanent magnet brings the risk of irreversible demagnetization fault to the PM machine. If the fault happens, the magnets will permanently lose a portion of their strength to generate magnetic flux, and consequently results in permanent degradation of machine power productivity and efficiency [49].

Figure 2-4 Demagnetization characteristics of NdFeB magnet

This mechanism of demagnetization can be depicted by using the second quadrant of B-H curve as shown in Figure 2-4, where the strength of magnetic field generated by magnets are described by its remanence (B_r) and coercivity (H_c). When the temperature increases, the magnitude of B_r and H_c will become smaller and move the curve towards the origin (red line to blue line). The load line L_1 and L_2 are dependent on machine operating condition, which will move towards left when the machine carries higher load (from position L_1 to L_2). Defining the intersection between load line and demagnetization curve as the load point, the demagnetization fault happens once the load point is below the knee point of the curve, and it cannot reverse to the position above the knee point again [50].

The simplest way to avoid demagnetization fault is by increasing the magnet size and magnetic strength to make sure the load point is always beyond the knee point, even when it experiences unexpected high temperature and load. However, it is not always acceptable since the high price of rare-earth material can dramatically increase the machine cost. In contrary, modern PM machines are required to operate at critical conditions to reduce the size of magnet. Thus, the PM machines and their drives must be carefully designed to avoid demagnetization fault for various machine operation conditions [5, 51].

2.3.2 Impact of stator winding short-circuit to demagnetization fault

There are several faults can result in machine irreversible demagnetization fault. From electrical engineer's point of view, the obvious cause of demagnetization fault is the inflow of excessive stator current, due to incorrect switching of the inverter,

overload at starting or lock state, and stator winding short-circuit fault [52]. These unusual operating conditions can move the load point of permanent magnets towards the knee point, and also the temperature rising due to the excessive resistive loss can reduce magnet's operating coercivity, which makes it more prone to demagnetization.

The stator winding phase-to-ground and phase-to-phase short-circuit fault are the cases which have been discussed mostly to cause irreversible demagnetization, because the short-circuit of entire phase would create overrated current on all numbers of winding turns [53]. A comparison between single-phase asymmetric fault and three-phase symmetric fault has been found in [54]. It shows that the single phase short-circuit fault can cause higher demagnetization stress than three-phase fault, and a suggestion in protective control prospect has been made that transfer single-phase short-circuit to three-phase short-circuit as soon as possible can reduce the irreversible demagnetization fault [55]. It has also been reported that the two-phase short-circuit is more dangerous than three-phase short-circuit and the seriousness of a two-phase short-circuit fault depends strongly on the phase angle of the voltage at the time when fault happens. Special attention must be paid to the inverter-fed PM machines as more current will be drawn to balance out the demagnetization loss when the fault happens. It can create more copper loss and rise the temperature which increases the chance of the machine to be severely damaged [49].

Unfortunately, the impact of inter-turn winding short-circuit fault to the demagnetization fault has been rarely found in the literature, because the overrating current

carried on a small portion of winding turns are believed to have limited influence to the machine flux. However, recent studies propose recommendation to investigate the impact of inter-turn winding short-circuit, as the irreversible demagnetization has been found [52]. In particular to the bar-wounded PM machine, the inter-turn fault can result in excessively high current due to the low winding inductance [56, 57].

2.3.3 Modelling of permanent magnet irreversible demagnetization

Since demagnetization fault of magnet is irreversible, the modelling techniques play an important role in designing and operation PM machines. In the meantime, it requires the modeling to deliver high accuracy in investigating the vulnerability of magnets under various machine operating conditions, so the process and result can be used as a reference or guideline to optimize machine design. Otherwise, fail to protect magnet from irreversible demagnetization can result in significant amount of development cost.

One of the conventional methods to investigate the demagnetization of permanent magnet is by using the linear analytical model [58]. This model is simple to design, which only requires the basic properties of magnet material, i.e., remanence, coercivity, and slope of BH curve. However, it usually neglects the material nonlinearity and only calculates the average flux density of permanent magnet. Another model based on permeance network is proposed to evaluate the performance of a partially demagnetized machine [59, 60]. This model takes into account the effect material nonlinearity and machine structural property. However, partial demagnetization of

magnet cannot be included into calculation [61]. It has also suggested that both of the models should be used only at the initial design step due to their low accuracy.

Nowadays, the majority of demagnetization analyses are carried out by using FEM. It is much more accurate than the analytical and linear models because all the machine particularities can be included, and also the operation of machine drives can be considered [49, 61]. With the help of this powerful tool, flux distribution inside the region of permanent magnet can be observed, and the most critical point which prone to be demagnetized in the magnet can be easily identified [62, 63]. In this case, the new challenge of using FEM analysis is to investigate irreversible demagnetization under machine safety-critical applications, which include:

- starting state and locked-rotor condition
- symmetrical stator three-phase winding short-circuit fault
- stator phase-to-phase short-circuit fault
- single phase inter-turn winding short-circuit fault

Among them, the study of starting and lock state are corresponding to the designated machine operation, whereas the stator short-circuit fault belongs to the machine operating accident. On one hand, the fault should be mitigated by the drives to reduce its impact to the machine productivity. On the other hand, irreversible demagnetization fault must be avoided so that production can be resumed once the fault is cleared. The related research works have been found in [5], where the influence of stator axial current to demagnetization during symmetrical short-circuit fault, as well as

the optimal rotor post and bridge thickness design is presented. A machine design to protect magnet from irreversible demagnetization under three-phase short-circuit condition is given in [64]. An improved flux wakening control algorithm to enhance machine performance and avoid irreversible demagnetization fault is proposed in [65].

The FEM analysis of these conditions requires external circuit coupled modelling, which, as introduced in section 2.2.3, is prohibitively inefficient in terms of computational speed. Especially for fault tolerant machine design, the repeated FEM modeling is always required to quantify the worse-case scenario [40, 57]. Therefore, a computationally efficient approach to assess the risk of demagnetization fault is also highly demanded.

2.4 The analysis of machine airgap eccentricity fault

2.4.1 Introduction of airgap eccentricity fault

Airgap eccentricity is a situation when there is unequal airgap length between rotor and stator. It can be caused by mechanical, magnetic, and thermal imbalances when machine is operating, or core ovality and misalignment due to imperfect manufacturing. The direct influence of airgap eccentricity is the irregular airgap flux distribution and the resultant unbalanced radial force. When the airgap irregularity is getting large, the unbalanced radial force may pull the rotor aside and cause rotor to stator rub which is also known as the unbalanced magnetic pull (UMP) [66].

Generally, machine airgap eccentricity can be categorized into the static eccentricity (SE) and dynamic eccentricity (DE). For SE condition, the minimum airgap length remains at the same place with respect to rotor motion, whereas the minimum length of airgap rotates with respect to rotor under DE condition. As a matter of fact, the DE and SE conditions co-exist at most of time, which is regarded as the mixed eccentricity (ME) fault. Usually, airgap eccentricity within 10% of airgap length is permissible, while the cases above this level are dangerous to machine operation, which are considered as fault [7].

Airgap eccentricity fault can be caused by many reasons including bent rotor shaft, unbalanced power supply, or the other types of fault such as defective bearing and rotor demagnetization [67, 68]. However, very little has been reported in literature concerns to find the cause of airgap eccentricity. Unlike the research for short-circuit fault or demagnetization fault which are taken from a wide angle including fault detection, machine design and its drives. The majority of research regarding to airgap eccentricity only focus on the early fault detection and machine performance analysis.

2.4.2 Machine performance analysis under airgap eccentricity

The performance analysis helps the researchers to understand the impact of airgap eccentricity to the machine. It is usually the first step in the development of fault diagnosis and fault-tolerant techniques. However, the experimental evaluation of machine performance under airgap eccentricity condition is very difficult, due to the small airgap length which is usually just several millimetres. In addition to the

weight of machine rotor, it is hard to mechanically move the shaft and maintain the eccentric distance in the desired range, especially when shaft tilt is included [69]. In this case, machine performance analysis usually requires reliable modelling techniques.

The FEM modelling is almost a non-optional choice for machine performance analysis under airgap eccentricity. It can include the mechanical deformation or physical change into the evaluation of machine performance, such as the airgap flux density evaluation using 3-D FEM for static and dynamic eccentricity conditions presented in [70]. Machine design using 2-D FEM analysis and performance comparison for different rotor structures under airgap eccentricity condition is found in [71]. The UMP effect due to different severity of airgap eccentricity is investigated in [72]. These findings of machine performance deviations under eccentricity condition can provide critical information for fault-tolerant machine design.

Generally, no matter for static or dynamic eccentricity conditions, FEM analysis for full machine model has to be used since the machine is no longer in symmetry and periodic boundary condition cannot be applied to reduce the computational load. It is difficult to couple this model with digital signal processor (DSP) for machine control. This has motivated some researchers to design accurate analytical models with less computational load. For example, a superposition method is used to calculate machine airgap flux density under airgap eccentricity condition in [73]. This model can be used together with FEM analysis to quickly predict machine performance. In [74], an analytical model is proposed to evaluate levitation force, which can be used

to design the rotor eccentricity compensation control for a bearing less PM motor. However, the FEM analysis is still used as a validation tool for these analytical models.

From reviewing the publications, the FEM analysis has been used as a common modelling tool to predict machine performance under airgap eccentricity condition. Due to the difficulty in conducting experimental validation, FEM analysis can be used as a validation tool if all the machine operating particularities are included. In general, analytical models are less accurate compared to FEM, but it is a good alternative if there is demanding in computational efficient machine performance evaluation.

2.4.3 Airgap eccentricity fault detection and condition monitoring

The definition of fault detection is synonymous to machine operation condition monitoring, where the latter more emphasizes online detection of machine operation abnormality. There are quite a number of methods proposed to detect machine airgap eccentricity fault. However, in reality, the fault detection technologies are hardly implemented especially for small- and medium-scale electrical machines.

2.4.3.1 Machine current signature analysis

Machine current signature analysis (MCSA) is the most widely discussed method for machine operation condition monitoring and fault detection [2]. It is attractive because this scheme only relies on the analysis of machine terminal current captured by its drive system. There is no requirement for additional signal capturing devices,

and the detection algorithm can also be implemented in the microprocessor of machine drives [75]. Typically, it has been reported that the SE and DE can result in variation of specific stator current spectral component, which is given by:

$$f_i = f_s \left(1 \pm \frac{k}{p} \right) \quad (2.6)$$

where f_i is the frequency component of fault indicator, f_s is the current fundamental frequency component, k is an integer, and p is the number of pole pair.

Fast Fourier Transform (FFT) is the most frequently used tool to extract the frequency component in stator current. It is simple and easy to implement for the machines operate at steady-state condition. For the machines operate at non-stationary conditions, such as machine load or speed variation, the FFT become unreliable due to the loss of time information [76]. In order to apply MSCA for non-stationary operating machines, more complicated current signal transform must be used. For example, the time-frequency analysis using windowed Fourier transform (WFT) has been introduced in [77]. This technique has been applied to a brushless direct current (BLDC) machine, but only for very low and limited speed change. Another technique, wavelet analysis, attempts to decompose the time series into time/frequency space simultaneously in processing stator current signal [78]. It has been successfully applied to detect DE for a BLDC motor under rapidly varying speed and load conditions.

One problem regarding the eccentricity fault detection problem is that the fault indicator in the stator current is exactly the same with the one induced by demagnetization fault, due to the same resultant magnetic field deformation [79]. Thus, the demagnetization fault and rotor eccentricity fault cannot be differentiated by only using MCSA technique. In summary, although the MCSA is of low cost and non-invasive to the machine, it still faces some issues which include:

- the fault signature can be identified only for a specific or very limited range of machine operating conditions
- the fault signature is differed for machine types and designs
- different types of machine fault could generate similar fault signatures

2.4.3.2 Magnetic field approach

Magnetic field is the medium of energy conversion in an electrical machine. In 1980s, machine axial leakage flux was firstly used for stator winding fault detection of an induction machine [80]. Since then, many publications can be found that use external magnetic flux (stray flux) for machine eccentricity fault detection [81, 82]. The search coil sensor, which is made of a few turns of copper wire, is usually placed at a stationary position outside the machine to capture flux. In case of eccentric air-gap, the minimal airgap length rotates towards the search coil and produce characteristic frequency components in the measured signal. The main advantage of this technique is that the external search coil is non-invasive to the machine and it is easy to implement, whereas the main drawback is that the stray flux is very weak, which depends on machine housing and ferromagnetic material.

To address this issue, the main flux based method, which captures the airgap flux using search coils wound at the tip of each stator tooth is further proposed in [83]. The advantage of this method is that only the magnitude of voltage fundamental frequency component is needed to indicate machine fault. Also, the result shows that the main flux based method is not only immune to the variations of machine operating condition, but also capable to detect multi-types of machine faults. However, the search coils wound at stator teeth are highly invasive to the machine airgap, and machine rotor usually requires to be dismantled in order to install search coils.

2.4.3.3 Mechanical effect approach

Some mechanical effects are unavoidable during machine operation, such as acoustic noise, vibration, thermal emission, as well as torque and speed which are machine nominal operating characteristics. The variation of these mechanical effects has been extensively used for machine operating condition monitoring and fault detection [7]. For airgap eccentricity fault, machine vibration and acoustic noise signals are especially useful due to the high sensitivity, but capturing these signals usually require extra sensor and signal processor, which increases the cost of productivity of the plant.

Machine vibration is caused by the resonance between excitation electromagnetic force and stator. The change of either MMF or airgap permeance caused by airgap eccentricity induces radial electromagnetic stress, which acts on the core and subjects the stator winding to harmonic vibration [84]. This vibration is further transmitted to the machine surface, which can be sensed by using strain gauge sensor

attached to machine frame [85]. The vibration can also be reflected in the bearing if airgap eccentricity is related to rotor shaft misalignment. In this case, the accelerometer can be used to monitor the accelerations of bearing, and this method has gained popularity due to low cost, high reliability, and low power consumption [86, 87]

The development of acoustic emission (AE) technology for machine fault detection and operation condition monitoring has been introduced in [88]. This technology is claimed to be particularly useful in detecting eccentricity and bearing related machine faults. However, the key problem is that the acoustic signal can be easily contaminated by environmental noises. So far, the AE based machine fault detection is not very popular and it is accepted by the fact that this technology is not fully explored until now [89]. With the development of acoustic sensors and intelligent filtering techniques, the AE based techniques still have huge potential for machine fault detection.

2.4.3.4 Fault indicator signal processing

For machine operating condition monitoring and fault detection, no matter for MCSA, magnetic field, or mechanical effect approaches, they are highly relied on signal processing techniques because the fault indicators are usually some specific spectrum components hidden in time-domain signals. The most common signal processing technique is the classical Fast Fourier Transform (FFT), which requires an analog-to-digital (A/D) sampler and a processor to convert sampled signal to frequency domain using FFT algorithm. However, the main disadvantage of the

classical FFT is the impact of side lobe leakage, which results in low spectral resolution [90]. In this case, the eigenanalysis based frequency estimators can be used to improve the resolution of signal spectrum. Another drawback of using classical FFT is that it is only suitable to process stationary signal. Hence, for non-stationary operating machines, it requires the wavelet analysis which is able to process signals with transitory characteristics such as drift, abrupt changes, and frequency trends [68].

The artificial intelligence (AI) techniques have been found in many publications for machine operation condition monitoring and fault detection. This technique is used to process the fault indicator data and especially helpful in decision making to identify fault. For example, if current signature is used as fault indicator, the AI algorithm can classify the collected current spectrum data into four categories according to the level of importance, and a spectral signature that falls outside these categories are marked as potential fault [91]. Typically, the artificial neural networks (ANN) and fuzzy logic systems are the most widely discussed AI techniques.

The ANN mimics human brain structure, which consist of neurons connected in complex multi-layers architecture. The neural training is the key procedure of using ANN, which uses a representative set of data to teach the network expert knowledge. After training, the ANNs could automatically detect machine operation anomalies by performing multiple inputs and outputs mapping [92]. This makes the ANNs particularly suitable to handle the nonlinear systems. So far, the ANN has been applied to detect almost all types of machine fault [93, 94]. However, the disadvantage of ANN is that this method only provides the optimistic solution in finding the fault, while the process in between the neurons is unknown. In contrast, the fuzzy logic

employs inferential system in a way close to humans thinking. It could transfer the linguistic and qualitative knowledge to the numbers and quantitative knowledge, which provides a simple way to interpret the fault detection and the decision can be made via fuzzy ‘if-then’ rules [95]. Unfortunately, this way of interpretation does not give an exact solution to the problems, while an exact solution is important for machine fault detection [96]. Even though the AI technologies have shown many advantages for machine fault detection, it is hardly accepted by industry due to lack of reliability. Perhaps the prospective research focus of this technique should be emphasizing the practical applications rather than theoretical analysis.

Until now, a substantial amount of techniques have been proposed for airgap eccentricity fault detection and operating condition monitoring. However, there is no specific technique can be considered as the best to solve this problem. In fact, the most techniques are hardly applied to serve industrial productivity, especially for the small and medium power electrical machines. Clearly, the cost-effectiveness is the major concern and it becomes a non-negligible factor in developing such technique. Table 2-2 is a brief comparison of the introduced technologies in this section. It does not include all the techniques introduced in the literature, but giving the general representative features of each method.

2.5 Summary

This chapter introduces the major types of electrical machine fault, the numerical methods for machine fault analysis, and the developed techniques for machine fault detection. This literature review of published works vary in a wide research scope,

because we believe a big picture is the best way to let the readers to be familiar with this research area. No matter for machine fault analysis or fault detection, the research should meet the end goal that to improve machine operation reliability and productivity. Specifically, this end goal can be achieved by either improving the fault-tolerant capability of machine itself, or early detection of machine deterioration for preventive maintenance.

From the literature review, it is noted that the FEM has taken the dominant position in the research of machine electromagnetic characteristics in the area of fault-tolerant machine design and faulty machine performance prediction. The results produced by this method can even be used for validation of other simulation methods because of its high accuracy. However the drawback of using FEM is the low speed in computation, and also the market-available FEM tools are expensive for routine maintenance and servicing. Therefore it will be of much help for machine and drive designers if a fast and convenient numerical tool can be provided for machine fault analysis.

In the prospect of fault detection, it can be seen that the major types of machine fault can actually be detected from a variety of methods. Nowadays, the problem regarding to machine fault detection is to use more cost-effective method, i.e. reduced number of expensive sensors and external signal analyzer, in a way to make them applicable for small and medium range electrical machines. Unfortunately, hardly any progress have been made so far, as the fact is that the most of electrical machines

are still operated, just like several decades ago, without any fault detection or condition monitoring functions.

In the following chapters, although machine fault is considered as a fairly mature research area, we would like to introduce some new ideas that from machine electromagnetism point of view to improve machine health monitoring.

Table 2-2 Comparison of the popular airgap eccentricity fault detection technologies*

Technology	Sensor and instruments required	Invasive to the machine	Skill requirement	Cost-effectiveness	Comments
MCSA	Current transformer	No	High	Moderate	Spectrum analysis required: use classical FFT for stationary operating machine; wavelet or other time-frequency transform for non-stationary operating machine
Airgap magnetic flux	Search coil	Yes	Moderate	Moderate	Only require the magnitude of signal fundamental component; usually require to dismantle machine and re-winding
Stray flux	Search coil	No	High	Moderate	Spectrum analysis required; high flexibility; available in industrial applications
Vibration	Accelerometer, strain gauge sensor	No	High	High	Spectrum analysis required; suitable for large industrial machines
Acoustics	AE sensor, noise filter	No	High	High	Spectrum analysis required; reliable AE sensor and environmental noise filtering required;
AI technology	Measured data and processor	No	Expert	Moderate	Can be a part of machine drive; knowledge of past information; reliability improvement required

* The content summarized is based on the literature reviewed in section 2.4.3

CHAPTER 3 MAGNETIC EQUIVALENT CIRCUIT MODELLING OF INTERIOR PM MACHINE

3.1 Introduction

As aforementioned, the numerical modeling by FEM is occupying the dominant position in evaluating machine performance because of its high accuracy. However, the drawback of this method is the low computation speed because it is difficult to implement if commercial software packages are unavailable. Therefore, another numerical modeling method by using MEC proposed in the 1960s [97] is revisited here.

Similar to FEM, the MEC method also use the machine material property and geometrical structure as the inputs, but the MEC method can be implemented with much less computation overheads. Thus, the MEC method is much faster in evaluating machine performance than FEM analysis. The implementation of MEC method also poses high requirement in the model design if high accuracy is demanded. There are several MEC models for various types of PM machines proposed in the last decade [98-100]. They all claim much faster computation speed with appealing accuracy compared to FEM analysis. Unfortunately, the MEC model for the popular V-type PM machine has not been found, and also most proposed model designs are complicated to be used as a convenient tool.

In this study, a generalized approach to design the MEC model for a large power V-type PM machine is proposed. The magnetic circuit is composed of four different types of flux tube. Also, the iron core nonlinearity and cross-coupling effects are considered in the model. Compared to FEM analysis, the proposed MEC model delivers promising accuracy and fast computation speed in predicting magnetic flux distribution and inductance under different load conditions, which makes it suitable to be adapted into a convenient computational tool for machine performance prediction.

3.2 Magnetic equivalent circuit method

3.2.1 Fundamentals of magnetic circuit

The magnetic circuit is used to describe and evaluate the magnetic flux flow in the electromagnetic device. As shown in Figure 3-1, a simple way to introduce magnetic circuit maybe by making a comparison with electric circuit because they have the analogous relations to each other. The corresponding analogous quantities can be found by in Table 3-1.

Figure 3-1 Comparison between simple electric and magnetic circuit

Table 3-1 Analogous quantities between electric circuit and magnetic circuit

Electric circuit	Magnetic circuit
Current, I [A]	Magnetic flux, Φ [Wb]
Current density, J [A/m ²]	Magnetic flux density, B [T]
Conductivity, σ [S/m]	Permeability, μ [H/m]
Electromotive force, ε [V]	Magnetomotive force, F [A]
Electric field intensity, E [Vm ⁻¹]	Magnetic field intensity, H [A/m]
Conductance, G [S]	Permeance, P [Wb/A]
Resistance, R [Ω]	Reluctance, R [H ⁻¹]

In the magnetic circuit, the direction of flux flow is perpendicular to the current source supply to the circuit, whereas the voltage and current flow is always in the same direction in electric circuit. Moreover, the current passing through the resistive conductor results in heat dissipation, while the energy supply to the magnetic circuit will not be dissipated but remains stored in the magnetic field [101]. Usually, the resistance of electric conductor is constant in electric circuit, while the reluctance of the magnetic conductor can be either constant or variable in the magnetic circuit.

In the most of electromagnetic devices, magnetic flux is un-evenly distributed throughout the magnetic conducting area. It is necessary to breakdown the area into smaller magnetic conducting elements in order to describe the flux distribution. These elements are also called the flux tubes which have different magnetic permeability and geometrical dimensions. The MEC model contains a network of these elements, and machine performance can be evaluated according to the flux-current relations obtained from the numerical solution of the model.

3.2.2 Magnetic characteristics of flux tube

Flux tubes are the fundamental component of magnetic circuit and they can be connected together to model the flux distribution of electromagnetic devices. The characteristic of each flux tube is described as permeance or reluctance, whose value is determined by its geometrical dimensions and material permeability. This relation can be represented by a typical cylindrical flux tube as shown in Figure 3-2, where the direction of flux path is perpendicular to the magnetic equal potential plane, u_1 and u_2 .

Figure 3-2 A cylindrical flux tube

Figure 3-3 Geometrical dimensions of commonly used flux tubes

The geometrical dimension of a flux tube is determined according to the shape of flux paths. In this case, many different shapes of flux tube are required in order to describe the flux distribution in the electromagnetic devices. As shown in Figure 3-3, the dimensions of commonly used flux tubes are depicted, where the arrow indicates the direction of flux passage.

For the radial flux electrical machines, rectangular and trapezoidal tubes are usually used to represent straight flux path, while arc tube can be used to represent flux path with curvature. If the material permeability is constant, the permeance of these flux tubes can be determined according to geometrical dimensions as following:

trapezoidal flux tube (a),

$$P = \mu l \frac{h}{w_1 - w_2} \ln\left(\frac{w_1}{w_2}\right) \quad (3.1)$$

trapezoidal flux tube (b),

$$P = \mu l \frac{w_1 - w_2}{h} \ln\left(\frac{w_2}{w_1}\right) \quad (3.2)$$

rectangular flux tube (c),

$$P = \frac{\mu(a \times b)}{l} \quad (3.3)$$

arc flux tube (d),

$$P = \frac{\mu l(r_1 - r_2)}{\pi(r_1 + r_2)} \times \frac{\theta}{360} \quad (3.4)$$

Depends on the material permeability and geometrical dimensions, the elements in the MEC model can be classified into constant flux tube, parametrical dependent flux tube, and inherently nonlinear flux tube. Constant flux tube is used for the magnetic conducting parts with constant permeability and rigid dimensions. The permeance of these flux tubes remains constant over machine transient conditions such as load and rotor position variation. In the PM machines, the commonly used materials with constant permeability can be found in Table 3-2.

Table 3-2 Material with constant permeability

Medium	Permeability μ [H/m]	Relative permeability μ/μ_0
Vacuum	$4\pi \times 10^{-7}$	1 (exactly)
Air	$1.25663753 \times 10^{-6}$	1
Aluminum	1.256665×10^{-6}	1
Copper	1.256629×10^{-6}	1
Neodymium magnet	1.32×10^{-6}	1.05
Samarium–cobalt magnet	1.32×10^{-6}	1.05

Parametrical dependent flux tubes are the ones with constant permeability but their dimensions are dependent of rotor motion. This type of flux tube is usually used to represent the flux paths in the machine airgap area. The characteristics of this type of flux tube can be illustrated by a schematic diagram in Figure 3-4. For the initial position (a), the stator flux tube P_i face towards the rotor tube P_j . If there is no leakage flux, the interconnection airgap flux path can be represented by an isosceles trapezoidal flux tube P_{ij} . When the rotor moves to position (b), a displacement can

be found between flux tube P_i and P_j , and the dimension of tube P_{ij} changes to the right angle trapezoidal flux tube. When the rotor displacement keep increasing to position (c), flux from tube P_j is no longer passing to the front side of tube P_i .

Figure 3-4 Airgap permeance with rotor motion

Machine stator and rotor are usually made from soft magnetic materials which can be easily magnetized or demagnetized. This type of ferromagnetic material is subjected to magnetic flux saturation. In other words, the flux density in this type of material cannot become higher even the external magnetic intensity keeps increasing. The permeance of flux tubes in the machine area made from soft magnetic material exhibits nonlinear relation with the strength of magnetic field even though the flux tubes have rigid dimensions. Since this nonlinear relation is determined by the material property which inherently exists in the machines, the corresponding elements in the MEC model are called the inherently nonlinear flux tubes [97].

3.3 MEC model for interior PM machine

This section will introduce the design approach of MEC model for a V-type interior PM machine as shown in Figure 3-5. The magnetic circuit for machine rotor, stator,

and airgap are presented separately in a generalized way of design, which can be extensively applied for other types of interior PM machine.

Table 3-3 Specifications of candidate interior PM machine

Specifications	Value
Power	2.2 MW
Speed	500 rpm
Stator outer diameter	890 [mm]
Stator inner diameter	650 [mm]
Rotor outer diameter	640.5 [mm]
Rotor inner diameter	270 [mm]
Stator back iron thickness	40 [mm]
Slot width	14.13 [mm]
Slot depth	80 [mm]
Stack length	1040 [mm]
Core steel	Silicon steel M19
Magnet grade	NdFeB 42SH

3.3.1 Specifications of the candidate machine

The interior PM machines have magnets buried into the rotor iron. This configuration increases the robustness of machine rotor to work against centrifugal force which is suitable for high speed operation [102]. There are twelve poles in the machine and each consecutive pole has symmetrical flux distribution. Machine specifications and dimensions required for MEC model design are included in Table 3-3.

Figure 3-5 Candidate interior type PM machine

3.3.2 Machine MEC model design

In order to improve the model computation efficiency, the symmetrical machine poles are represented by applying the odd-periodic boundary condition so that only one pole of machine is required. The magnetic circuit is designed based on the idea of using minimum number of flux tubes to capture the flux flow. It assumes machine is unloaded or only the d-axis MMF is exerted, which results in a balanced magnetic flux distribution and the following conditions are held:

- (a) The main flux flows out through airgap facing the two magnets.
- (b) The leakage flux through left and right holders are evenly distributed.
- (c) The flux flow through the centre of two magnets is contributed evenly by two magnets.
- (d) The leakage flux comes from airgap through this region is nil.
- (e) The flux flows from left magnet to its adjacent pole is in symmetrical with the flux flows into the right magnet.

Figure 3-6 Magnetic circuit design of machine rotor

In this way, the magnetic circuit for machine rotor can be represented in Figure 3-6, where two layers of horizontal flux tubes in combination with three vertical layers of flux tubes are used to capture the flux in the rib area. The majority of rotor flux will pass through the airgap and primarily return to the adjacent poles, while a small amount of flux can leak from magnet holder P_{r_holder} and rotor center P_{r_center} to the opposite polar of magnet. The area near rotor shaft has low flux density, where the flux is captured by trapezoidal flux tubes P_{r_rear} and P_{r_aux} .

The permanent magnet is made from hard magnetic material. It is equivalent to a rectangular flux tube P_{r_magnet} with fixed permeability which can be found from the B-H curve given in Figure 3-7. Permanent magnet is also the active source of magnetic circuit, and the corresponding MMF can be calculated as:

$$F_{pm} = H_c l_m \quad (3.5)$$

where F_{pm} is the MMF generated by magnet, H_c is the coercive force of magnet, and l_m is the length of magnet in the magnetization direction.

 Figure 3-7 The 2nd quadrant of B-H curve for NdFeB 42SH magnet

The stator of each machine pole has six teeth with exactly the same geometry. For simplification purpose, the stator is further divided into three modulars and each of them contains two stator teeth, as shown in Figure 3-8. The tooth main area is divided into three trapezoidal flux tubes. Between the tooth, leakage flux tube P_{s_leak} and coil flux tube P_{s_coil} are intercepted to capture the circumferential leakage flux. Flux changes from vertical direction to horizontal direction at the tooth back joint area which is divided into three linkage flux tubes P_{s_link} .

Figure 3-8 Machine stator magnetic circuit

Tooth tip has high flux gradient where flux may leak from the side of tooth tip. It is captured by the fringe flux tube P_{s_fringe} which is composed by an arc flux tube and a rectangular flux tube, as seen in Figure 3-9.

Figure 3-9 Flux tube to capture tooth fringe flux

The corresponding permeance of the fringe flux tube is calculated by:

$$P_{fringe} = \frac{2\mu l}{\pi} \ln\left(1 + \frac{\pi a r_g}{2g}\right) \quad (3.6)$$

where r_g is the average radius of the rectangular part.

The airgap interconnect the rotor and stator magnet circuit, which requires a large number of flux tubes to capture the flux passage in this area. Also, it is the most critical part to determine model accuracy, though the length of airgap is only a few millimetres.

As shown in Figure 3-10, where (a) is the initialized airgap magnetic circuit which is determined according to the relative position of rotor and stator boundary flux tubes. Each of the stator nodes is connected to at least two rotor nodes. This multiple

rotor and stator interconnections primarily describe the flux paths in a physical meaningful way. Due to the high flux density gradient in the airgap, an additional layer of flux tubes are designed to increase the model accuracy. As shown in (b), the initialized radial flux tubes are evenly split into upper and lower layer of flux tubes. In the middle of the two layers, the nodes are created and extra flux tubes can be added between the nodes to capture the circumferential flux passage.

Figure 3-10 Airgap magnetic equivalent circuit

3.4 Numerical solution of MEC model

The elements introduced in the magnetic circuit design have different permeance and some of them are subjected to the flux saturation. This section introduces the method to solve this numerical model, which includes the application of odd-periodic boundary, the equivalent solution derived from Maxwell's equations, and the iterative approach to hand model nonlinearity.

3.4.1 Odd-periodic boundary condition

Combining rotor, stator, and airgap magnetic circuits together, the overall MEC model of this PM machine is shown in Figure 3-11. This model contains 137 elements, including 41 inherent nonlinear elements, and 96 constant elements.

Figure 3-11 MEC model of the candidate PM machine

As aforementioned, odd-periodic boundary condition is applied to the MEC model, where the magnetic potentials on the left and right boundary have the same magnitude but are in opposite direction [60]. This relation of magnetic potential can be represented by equation:

$$A_{z_left} = -A_{z_right} \quad (3.7)$$

The implementation of this boundary condition can be illustrated by using a small part of MEC model as shown in Figure 3-12, where (a) and (b) are the typical loop and nodal magnetic circuit in the model, respectively. In (a), the boundary flux path

is substituted by the flux path number 7 on the other boundary. In the same way, as shown in (b), a nodal magnetic circuit contains the circumferential flux path number 30 from the other boundary.

Figure 3-12 Illustration of odd-periodic boundary condition

3.4.2 Calculation of magnetic flux

Magnetic flux will be induced when the MMF sources are applied to the MEC model.

It can be calculated according to the governing equation:

$$\Phi = P \times F_{mmf} \quad (3.8)$$

$$P = \frac{1}{R} \quad (3.9)$$

where Φ is the magnetic flux; P is the permeance of flux tube, R is the reluctance of flux tube; F_{mmf} is MMF source.

Taking into account of machine load, the MMF sources of MEC model are contributed by both rotor permanent magnets and three phase winding. Unlike the permanent magnet whose MMF is along with magnetization flux, winding coils are

located inside the stator slot with the current direction orthogonal to the radial flux. The relation between the magnetic flux and winding current is given by the Faraday's law represented in Maxwell's equations:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (3.10)$$

where H is the flux intensity; J is the current density among the magnetic field; D is the displacement current.

In the magnetostatic field, the displacement current equals to zero which can be removed from this equation, and the new expression in the integral form is written as:

$$\int_s (\nabla \times H) dA = \int_s J dA \quad (3.11)$$

where, A is the corresponding magnetic field area.

However, it is still difficult to implement area integration of magnetic flux in the MEC model, so the Stokes theorem is introduced to transform the area integration problem to the line integration problem as given by:

$$\int_s (\nabla \times H) dA = \oint_c H dl \quad (3.12)$$

where c is the contour of the magnetic field area.

Combining equation 3.11 and 3.12, the relation between the magnetic flux pass through the contour and the current MMF source can be represented by equation:

$$\oint_c H dl = \int_s J dA \quad (3.13)$$

Therefore, according to equation 3.13, the stator MMF generated from the slot area is equivalent to the integration of magnetic flux along the corresponding magnetic circuit loop.

Figure 3-13 The general form of magnetic circuit loop and node in the MEC model

Because of the analogous relations between electric circuit and magnetic circuit, the well-known Kirchhoff's Law is applied to all the loops and nodes to calculate the flux of each of the 137 paths in the MEC model. In Figure 3-13, (a) is a typical magnetic circuit loop consists of m number of flux paths, the permeance of each flux path is represented by P_1 , P_2 , P_3 , and till P_m , the MMF generated from this loop is represented by F_{mmf} . According to the Kirchhoff's Voltage Law (KVL), their relation of flux and MMF source can be represented by:

$$\frac{\Phi_1}{P_1} + \frac{\Phi_2}{P_2} + \frac{\Phi_3}{P_3} + \dots + \frac{\Phi_m}{P_m} = F_{mmf} \quad (3.14)$$

Likewise, in (b), the node contains n number of flux paths, according to the Kirchhoff's Current Law (KCL), the summation of the flux goes into a node will be equal to the flux come out of it, which can be represented by:

$$\Phi_1 + \Phi_2 + \Phi_3 + \dots + \Phi_n = 0 \quad (3.15)$$

The algebraic equations are obtained by applying KCL and KVL to all of the loops and nodes in the MEC model, which can be written in the matrix form as:

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \vdots \\ \Phi_{137} \end{pmatrix} = \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_{137} \end{pmatrix} \begin{pmatrix} Y_{1-1} & Y_{1-2} & \dots & Y_{1-137} \\ Y_{2-1} & Y_{2-2} & \dots & Y_{2-137} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{137-1} & Y_{137-2} & \dots & Y_{137-137} \end{pmatrix}^{-1} \quad (3.16)$$

where $[\Phi]$ is the matrix consist the flux pass through each path, $[Y]$ and $[B]$ are the sparse matrix consist the reluctance and MMF sources of the model, respectively.

3.4.3 Iterative approach to solve model nonlinearity

The inherent nonlinear problem is addressed by using an iterative approach to solve the model. Ideally, to implement the full detailed B-H curve of silicon-steel material will deliver the most accurate result, however it will require long computation time which reduce the model computational efficiency. Instead, the original B-H curve is simplified by a piecewise linear approximation curve, as shown in Figure 3-14.

Figure 3-14 The B-H curve of the silicon-steel material for stator and rotor iron

The flux density between the data points in the modified curve is described by equation:

$$B = B_i + \frac{B_{i+1} - B_i}{H_{i+1} - H_i} (H - H_i) \quad (3.17)$$

Material permeability is obtained by taking the first derivative of each linear segment. In iteration, a weighted average method is used to update the permeability for nonlinear elements, which is described as:

$$\mu_{updated} = (\mu_{new} \times G_{new}) + (\mu_{old} \times G_{old}) \quad (3.18)$$

$$G_{old} + G_{new} = 1 \quad (3.19)$$

where G_{new} and G_{old} are the weighted average gains for new and old permeability, respectively. The new permeability μ_{new} is found by interpolation method from the B-H curve. The updating permeability $\mu_{updated}$ is determined by equation 3.18, which

is used to compute the corresponding flux intensity H and density B for the next iteration. This procedure to solve MEC model is described by a flow chart as shown in Figure 3-15, where the initial permeability is determined by the first data point in the piecewise linear B - H curve. The iteration stops when the error between the two iterations is smaller than the criteria.

Figure 3-15 Flow chart of the procedure to solve MEC model

3.5 Result and analysis

For inverter-fed PM machines, the stator current can be regulated to a specific value in order to obtain the optimal machine operating performance. Typically, by using the vector control technique, three phase winding current is controlled to align with the q -axis for maximum torque generation [103]. The relation between the d - q axis

current can be represented by current limit circle given in Figure 3-16, where γ is the rotor reference angle with respect to q-axis. The proposed MEC model is used to evaluate machine flux distribution and inductance at different operating points under open circuit and loaded conditions.

Figure 3-16 Machine operating point in d-q axis plane

The model input MMF sources are calculated from the phase current and the number of turns in the slot, as given by:

$$F_{mmf} = N_{turn} I \quad (3.20)$$

The phase flux linkage including both magnetization and leakage flux can be predicted according to the stator yoke flux path from the MEC model, as given by:

$$\lambda_x = (\text{sgn})\Phi_{x1} + (\text{sgn})\Phi_{x2} \quad (3.21)$$

where λ_x is the flux linkage of any phase, sgn represents the current direction of the corresponding phase which can be either of +1 or -1, Φ_{x1} and Φ_{x2} are the yoke flux of corresponding phase as each phase occupies two slots per pole.

The phase back EMF is determined from the rate of change of phase flux linkage by:

$$e_x = \frac{d\lambda_x}{dt} \quad (3.23)$$

The d-q axis inductance can be obtained from the obtained flux-current relations as given by:

$$L_d = \frac{\lambda_d - \lambda_{pm}}{I_d} \quad (3.24)$$

$$L_q = \frac{\lambda_q}{I_q} \quad (3.25)$$

To validate the MEC model, the predicted flux and inductance are compared with the result obtained by using commercial FEM package Quickfield. This package allows the user to obtain the average flux potential on all the machine components, which is suitable to validate the average flux obtained by MEC model. Ideally, the validation of MEC model is achieved by experimental tests of machine operations. However, due to the high flexibility and accuracy, FEM analysis is also used to validate MEC model design [104, 105]. Typically, the deviation between experimental test and FEM analysis is less than 10% if sufficient number of elements have been applied [106, 107].

Under open circuit condition, the distribution of airgap flux density is shown in Figure 3-17, where the V-type magnet configuration makes the flux concentrated at the center of the airgap between 5° to 25° mechanical angle with respect to rotor coordinate. This prediction is also valid for the magnetic flux pass the stator teeth as

given in Figure 3-18, where the flux pass the two teeth at the side is much lower than the ones at the center. Machine phase flux linkages are given in Figure 3-19, where the maximum deviation compared to the FEM analysis is 7.8% for the peak values. These figures indicate that the deviation of flux evaluated by the MEC model is less than 10 percent compared to FEM analysis under open circuit operating condition.

Figure 3-17 Airgap spatial flux density under open circuit condition

Figure 3-18 Tooth flux under open circuit condition

Figure 3-19 Phase flux linkage under open circuit condition

Under loaded conditions, flux distribution is off-centred as the resultant of interaction between rotor magnetization flux and stator winding induced flux. The airgap flux density is no longer balanced to the rotor coordinate center, as shown in Figure 3-20. When the rotor reference angle is 75° under rated operating condition, the maximum deviation of tooth flux is 7.1% compared to FEM analysis at the tooth located at 17.5° with respect to rotor coordinate, as shown in Figure 3-21.

Figure 3-20 Spatial airgap flux density under 75° rotor reference angle under rated operating condition

Figure 3-21 Tooth flux under 75° rotor reference angle under rated operating condition

Figure 3-22 to Figure 3-24 show the flux pass through stator teeth when the rotor reference angle varies from 0° to 90° in the step of 18° under rated condition. It can be seen that a good agreement has been gained compared to FEM analysis, the MEC model effectively capture the resultant flux distribution at different stator flux positions. The reason to choose tooth flux for comparison is due to the convenience for FEM analysis to work out the average flux via the average flux potential.

Figure 3-22 Flux pass through tooth 1 and 2 under different load conditions

Figure 3-23 Flux pass through tooth 3 and 4 under different load conditions

Figure 3-24 Flux pass through tooth 5 and 6 under different load conditions

The d-q axis inductance evaluated by the proposed model is shown in Figure 3-25, where the d-axis inductance is obtained with the presence of only d-axis current and q-axis inductance is obtained with the presence of only q-axis current. Magnetic fluxes in the d-axis pass through low permeability central area so that the d-axis inductance is less affected by magnetic saturation because of large magnetic resistance. The q-axis inductance is greater than d-axis inductance, since flux pass

through higher permeability area is significantly affected by magnetic saturation. Due to magnetic cross-coupling, the d-axis inductance evaluated by MEC model exhibits higher accuracy than the q-axis inductance. Nevertheless, the proposed MEC model still gives promising accuracy in evaluating machine inductance as the maximum error is 7.8% compared to FEM analysis.

Figure 3-25 Machine d-q axis inductance at different current angle

The elapsed time required by MEC model is more than 80 times faster than FEM analysis as shown in Table 3-4. This time is counted by the software MATLAB and commercial FEM package on the same computer. There are slight differences in the time counted for different loaded conditions, where the impact is mitigated by taking the average value of all cases.

Table 3-4 Computation time comparison with FEM analysis and MEC model

	FEM analysis	MEC model
Number of elements	7812 per pole	137 per pole
Computation time	9 seconds	0.1092 second

3.6 Summary

In this chapter, a MEC model for a large power interior PM machine is proposed. This model is designed based on machine geometrical data and material electromagnetic property so that the nonlinear magnetic saturation effect is considered in predicting machine flux distribution and operating inductance. The model is designed in a generalized procedure, where machine stator, rotor and airgap magnetic circuit are composed in a modular manner, so it can be extensively used for various types of PM machine with a V-type magnet configuration.

By comparing with FEM analysis, the proposed MEC model presents the deviation less than 10% with the computational speed more 80 times faster, which makes it very suitable to work as a fast numerical tool to evaluate machine operating flux linkage and inductance, in the presence of magnetic saturation. Nevertheless, the main limitation by using this method is that the MEC model is designed at a fixed rotor angular position, and therefore the airgap magnetic circuit has to be redesigned when incorporating rotor motion.

CHAPTER 4 FAULTY MACHINE PERFORMANCE PREDICTION BY A LUMPED MEC MODEL

4.1 Introduction

Machine performance prediction under inter-turn winding short-circuit faulty conditions has attracted considerable attention since it provides important information to improve machine fault-tolerant capability. Usually, it can be achieved with high degree of accuracy by FEM modeling [30-32, 108, 109]. However, the FEM is slow in computation, and also the market-available software packages may not be available for machine health monitoring and prognosis service providers.

In this chapter, we use the MEC method introduced in last chapter and apply it for machine performance prediction under inter-turn winding short-circuit fault. Another type of PM machine is used in this study for the purpose to further validate the generalized model design approach. A series of MEC models are combined into a lumped model to mimic the effect due to rotor motion. Machine inductance, flux linkage, and electromagnetic torque are evaluated under both healthy and winding short-circuit conditions. By comparing with FEM analysis, the model presents appealing accuracy but much less required computation time. Thus, it can be used to continuously assessing machine performance in a much convenient and cost-effective way.

4.2 Modeling of PM machine with double layer winding

4.2.1 Candidate PM Machine

Figure 4-1 shows the layout of the candidate PM machine. It has double layer distributed winding with one slot chorded. Rotor magnets are buried into rotor poles which are separated by a horizontal airgap. This configuration exhibits strong saliency in d-q axis. Machine geometrical data and material property required for MEC model design are given in Table 4-1. For stator short-circuit fault, the minimum a turn-to-turn short-circuit is the beginning of partial winding short-circuit fault, which is most likely due to ageing of insulation caused by temperature stress, moisture, mechanical stress, etc. during machine operating. The overrated current flow in the faulty turns will induce unexpected flux in the machine, but the influence is dependent of machine winding type, load condition, and fault location [30, 57, 110].

Figure 4-1 Layout of the candidate interior PM machine

Table 4-1 Design data and specification of the candidate PM machine

Parameters	Value
Stator outer diameter	315 [mm]
Stator inner diameter	232 [mm]
Rotor outer diameter	230 [mm]
Shaft diameter	78 [mm]
Axial length	250 [mm]
Number of phase	3
Number of pole	12
Number of turns per pole per phase	10
Speed	1500[RPM]
Power	100kW
Magnet relative permeability, μ_r	0.8
Magnet coercivity, H_c	1248000 [A/m]

Figure 4-2 Comparison of stator flux density (T) of different fault severity. (a) healthy case, (b) 25% coil fault and x2 current, (c) 50% coil fault and x2 current, (d) 50% coil fault and x4 current.

In this study, we assume machine terminal current is regulated by fault mitigation control and the overrated current of partial winding short-circuit is four times higher than the healthy value [56]. Figure 4-2 illustrates the stator tooth flux density obtained by FEM analysis for localized overrating current where the fault location is highlighted. It can be seen that the flux induced by faulty coil enhances the main flux passing through the neighbouring tooth in the same direction, whereas it weakens the flux passing through the other neighbouring tooth in the opposite direction. Flux density changes at non-neighbouring teeth can also be found. Moreover, if the overrated current is too high, the induced flux may pass through machine airgap and demagnetize the magnet, but this situation is not considered in this study [111].

4.2.2 Lumped MEC model design

The candidate machine contains twelve poles where the magnetic flux is symmetrically distributed. For the initial rotor position (defined as 0°) shown in Figure 4-1, rotor magnetization flux pass through the airgap will mainly go through the four teeth located in the middle, and teeth at the side only receive a small portion of flux. Accordingly, we can describe the flux passage using magnetic circuit as shown in Figure 4-3.

The elements representing stator and rotor part have rigid dimensions but the corresponding permeability changes nonlinearly with respect to flux level. The highlighted airgap area interconnects rotor and stator, which is the most sensitive part of circuit to determine model accuracy due to high flux density gradient. Hence

a circumferential layer of elements is added in the middle of airgap to enhance model capability to capture circumferential flux passage.

Figure 4-3 MEC model for the candidate machine

Taking into account the rotor motion, since stator-rotor relative position appears periodically in every 5° , the other four MEC models are designed to describe the consecutive magnetic flux distribution for every 1° rotor angular position, as shown in Figure 4-4. In model design prospect, because rotor and stator elements have constant dimensions, the tricky part is the airgap between rotor poles. However, for any relative rotor position as shown in Figure 4-5, magnetic circuit can be summarized into two situations, where (a) when rotor rib confronts with stator tooth and (b) when rotor pole gap confronts with stator tooth. The corresponding permeance of flux paths can be calculated from the arc tube given in (c) and (d) by equations:

$$P_1 = \mu_0 \left[\frac{4}{\pi} + \frac{2(r_2 - r_1)}{g} \right] L \quad (4.1)$$

$$P_2 = \mu_0 \frac{2}{\pi} \ln \left[\frac{g + 0.5\pi r_2}{g} \right] L \quad (4.2)$$

where μ_0 is the air permeability, L is the axial length of machine. g is the airgap length; r_1 and r_2 are dependent of arc flux tube at the corresponding rotor position.

Figure 4-4 Lumped models of candidate machine for different rotor positions. (a) relative rotor position 1°, (b) relative rotor position 2°, (c) relative rotor position 3°, (d) relative rotor position 4°.

Figure 4-5 Airgap flux tubes of a typical rotor position

4.2.3 Machine performance predictions

To validate the proposed MEC model, the PM machine is assumed working under steady-state condition. The d-axis current is given a small negative value which equals to -5A to test the d-axis flux capturing of MEC model, as the negative d-current is usually used in the flux weakening control. The speed and load variation is not considered in the study, because they just result in the excitation current variation from the model's point of view. In this case, the flux induced by machine MMF is contributed by both stator winding and rotor magnet, which are assigned to the MEC model according to the actual position in the machine. Taking into account the turns carrying short-circuit current, the MMF contributed by stator winding can be calculated by

$$F_w = I_h \times N_h + I_f \times N_f \quad (4.3)$$

where I_h is healthy current; N_h is number of healthy turns; I_f is fault current, N_f is number of short circuit turns.

The MMF of permanent magnet is calculated according to the remanence and the size of magnet, which is given by:

$$F_m = \frac{B_r l_m}{\mu_r \mu_0} \quad (4.4)$$

where B_r is the remanence of magnet material, l_m is the depth of the magnet, μ_r and μ_0 are the permeability of magnet and free space, respectively.

Machine operation parameters can be derived from current-flux relations upon solving the MEC model. Assuming all the flux will eventually pass through the stator back iron area, phase flux linkage for double layer winding configuration can be calculated as:

$$\lambda_x = \lambda_{xb} + \lambda_{xt} = (\Phi_{bx1} + \Phi_{bx2}) + (\Phi_{tx1} + \Phi_{tx2}) \quad (4.5)$$

where λ_x is the flux linkage of any phase, λ_{xb} and λ_{xt} are the flux induced by bottom and top layer winding, and Φ_{bx1} , Φ_{bx2} , Φ_{tx1} , Φ_{tx2} are the flux pass through the back yoke of each corresponding slot, respectively.

The phase self- and mutual inductance can be derived by flux linkage and the corresponding excitation current according to the equation:

$$L_x = \frac{\lambda_x - \lambda_{m-x}}{I_x} \quad (4.6)$$

$$M_{xy} = \frac{\lambda_x - \lambda_{m-x}}{I_y} \quad (4.7)$$

where L_x and M_{xy} are the self- and mutual inductance of any phase, λ_x and λ_{m-x} are the phase total flux linkage and flux linkage induced by rotor magnet, I_x and I_y are the excitation current that induce self- and mutual inductance.

The d-q axis flux linkage can be converted by using the a-b-c to d-q reference frame as shown in Figure 4-6, and the corresponding transformation equations are given as:

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \times \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \quad (4.8)$$

where θ is the initial angle for abc-to-dq transformation.

This angle is usually used to determine the required current value for machine vector control purpose. Here, the angle will change with rotor motion to find the corresponding flux and inductance change due to different rotor position. Machine electromagnetic torque can be expressed by equation:

$$T_e = \frac{3}{2} p I_q (\lambda_m + (L_d - L_q) I_d) \quad (4.9)$$

Figure 4-6 Transformations of variables in a-b-c stationary frame to d-q arbitrary frame

4.3 Result analysis and comparison with FEM

The PM machine performance is evaluated by both lumped MEC model and 2-D FEM analysis, under open circuit, loaded, and partial inter-turn winding short-circuit conditions. Three dimensional effects, such as end winding leakage flux and axial shaft leakage flux, are neglected. For the stator winding turn fault, it is assumed that the stator phase current is still regulated by machine drive and the effective number of turns is not affected [112, 113].

4.3.1 Machine performance evaluation by Lumped MEC model

Machine phase flux linkage is solely contributed by rotor magnets under stator open-circuit condition. This study can be used to test the basic accuracy of the proposed MEC model. Figure 4-7 presents the three phase flux linkage obtained by lumped MEC model which exhibit sinusoidal waveform and the result shows good agreement compared to the FEM analysis. In Figure 4-8, the obtained phase flux linkage

is converted into d-q axis flux linkage, it can be seen that rotor flux linkage is aligned to stator d-axis which satisfies the primary machine design configuration.

Figure 4-7 Phase flux linkage for open circuit condition

Figure 4-8 d-q axis flux linkage for open circuit condition

In the presence of stator current, machine flux distribution will be deviated from the unloaded condition, which is more challengeable for MEC model to capture. Here, stator d- and q- axis current are set to -5A and 100A respectively, which is equivalent to an ordinary vector control configuration. Figure 4-9 presents the phase flux linkage evaluated by lumped MEC model and FEM analysis. It can be seen that the magnitude of phase A (black color) flux is almost identical with the open circuit condition, whereas the magnitude of phase B (blue color) and phase C (red color) flux linkage change significantly. This is due to the relative small d-axis current aligned to phase A. In contrast, the flux induced by stator q-axis current is much higher, which result in significant change of phase B and phase C flux linkages.

Figure 4-9 Flux linkage under machine loaded condition ($I_d=-5A$, $I_q=100A$)

Figure 4-10 presents the corresponding d-q axis flux linkage, where both FEM analysis and MEC model indicate that the d-axis flux reaches to the peak value when rotor rotates 15° mechanical angle (90° elec. angle). The peak q-axis flux linkage

appears at the initial rotor position but it becomes smaller and reaches to the minimum value when rotor rotates 15° . The variation of d-q axis inductance with respect to the rotor position is shown in Figure 4-11, where the lumped MEC model exhibits higher accuracy in predicting q-axis inductance compared to d-axis inductance. The maximum percentage error is about 16% at 100° for d-axis inductance, which is due to the high relative error, as the magnitude of d-axis current is very small. Overall, the performance of lumped MEC model is still acceptable as the trend of parameter variation can be easily recognized.

Figure 4-10 d-q axis flux linkage under machine loaded condition ($I_d=-5A$, $I_q=100A$)

Figure 4-11 d-q axis inductance for loaded condition ($I_d=-5A$, $I_q=100A$)

Under the same loaded condition, when 25% of coil located at center (15° mech. angle) of phase C is subject to short-circuit fault, the phase and d-q axis flux linkages are shown in Figure 4-12 and Figure 4-13, respectively. The faulty turns induce extra flux which is mixed with original flux distribution. Although the net increment is relatively small compared to the original flux distribution, it can be seen that the flux linkage curve is not as smooth as the healthy condition.

Figure 4-12 Machine phase flux linkage under phase C short-circuit condition

Figure 4-13 Machine d-q axis flux linkage under phase C short-circuit condition

This extra MMF results in higher deviation in predicting machine axial inductance as shown in Figure 4-14, where the maximum percentage error reaches to 19% for the d-axis inductance. Nevertheless, compared to FEM analysis, the lumped MEC model still deliver promising accuracy for both healthy and faulty conditions.

Figure 4-14 Machine d-q axis inductance for phase C winding fault

Figure 4-15 Machine torque under healthy and phase short-circuit condition predicted by (a) lumped mec model, (b) FEM analysis.

The electromagnetic torque predicted by lumped MEC model and FEM analysis under faulty condition is shown in Figure 4-15. It is hardly seen any difference between the torque under healthy and faulty conditions no matter by using either lumped MEC model or FEM analysis, because the limited influence of short-circuit on d-axis flux linkage. Moreover, electromagnetic torque is mainly induced by the coupling of rotor magnetization flux and stator q-axis current, so the short-circuit will not affect machine torque if stator terminal current can be regulated to the healthy level.

4.3.2 Computation time required by lumped MEC model and FEM analysis

Table 4-2 compares the elapsed time required by FEM analysis and proposed lumped MEC model. It can be seen that the lumped MEC model is more than 10 times faster than FEM analysis.

Table 4-2 Computation time required by FEM analysis and lumped MEC model

	FEM analysis	Lumped MEC models
Number of elements	15634	143(average)
Steps	30	30
Elapsed time	405 seconds	33 seconds

Also, it is possible to optimize the meshing settings to further reduce the time required by FEM analysis, but the effectiveness is negligible and the meshing optimization itself is time-consuming. Although the commercial FEM packages provide easy access to build machine model via computer-aid-design (CAD) to reduce the preparation time, they are still too expensive for ordinary user to conduct machine fault analysis. Considering the cost and speed advantages combined with

promising accuracy, the lumped MEC model is a suitable option for quick faulty machine performance prediction.

4.4 Summary

This chapter presents a lumped MEC model to predict the operation characteristics for a double layer winding PM machine with salient rotor. By using the generalized model design approach, the MEC model for different rotor positions can be obtained in a much convenient way and also exhibits high degree of accuracy in representing machine electromagnetic characteristics. In addition to the ordinary machine performance prediction, the lumped MEC model is applied to investigate the influence of stator winding short-circuit fault and the results reveal good agreement compared to FEM analysis, which prove the usefulness of MEC model as a convenient tool for developing machine fault mitigation techniques.

Although the commercial FEM packages make much progress in reducing the computation time, the speed of MEC model is still much faster (>10 times) from our studies. Besides, the high expenses of commercial FEM software licenses may prohibitive to the machine servicing and maintenance sector. Hence it is of much interest to explore these potential applications of MEC models.

Additionally, in general, the stator inter-turn winding short-circuit fault will not result in severe machine damage, unless it has deteriorated to phase-to-phase or phase-

to-ground short-circuit fault which may cause catastrophic machine failure. The research of machine phase short-circuit is still under way to extend the lumped MEC model to external circuit coupled configurations.

CHAPTER 5 IRREVERSIBLE DEMAGNETIZATION FAULT ANALYSIS OF INTERIOR PM MACHINE UNDER INTER-TURN WINDING SHORT-CIRCUIT CONDITION

5.1 Introduction

For inverter-fed PM machines, the impact on the faulty phase caused by inter-turn winding short-circuit fault can be mitigated by limiting that phase current upon detection [114]. However, the resulting current flow in the faulty turns may still be excessive and the magnitude of this fault current can be many times greater than the rated phase current value [56]. This additional current will increase the stator magnetization flux and put the machine under the risk of irreversible demagnetization of the permanent magnets. So far, this risk has not been adequately addressed in most studies dealing with short-circuit fault mitigation.

This chapter presents a novel approach to quickly assess the risk of irreversible demagnetization for a bar-wound interior PM machine under inter-turn winding short-circuit fault. Moreover, the conventional time-consuming transient finite element analysis is substituted by using much more efficient magnetostatic analysis incorporated with a current prediction analytical model. Although some essential knowledge is required to quantify magnetic flux, the computation time required is much less when compared with conventional transient FEM analysis approach. In

this way, the presented approach can be used as a convenient tool to assess irreversible demagnetization under winding short-circuit condition.

5.2 Critical PM machine operation condition of demagnetization

The assessment of demagnetization fault is dependent of each individual machine because the flux distribution is related to machine structure and the material used. Figure 5-1 presents the flux density contour plot of the candidate machine and its zoom-in on the magnets' flux distribution under open circuit condition, where the direction of remanent induction flux is perpendicular to the long sides of magnet cavity. For this V-type magnet configuration, the rotor flux travel from the two magnets opposite to each other at the center of rotor rib area, and the majority of rotor flux will pass from the airgap through the stator iron to the neighboring magnet with opposite polarity.

Figure 5-1 Flux density distribution under open circuit condition

To operate the machine, the relative position of rotor and stator magnetic field is regulated by coordinate control of stator winding current, in a way the appropriate stator flux can interact with rotor flux to generate the required machine torque and speed. Typically, with the help of field oriented control (FOC), the stator flux is decoupled into d- and q- axis component, which respectively determines machine reactive and active power. Figure 5-2 shows the corresponding a-b-c and d-q axis current under rated operating condition, where the peak value is 5826A. Irreversible demagnetization should not happen for any of the load conditions if the machine is well-designed.

Figure 5-2 Synchronous frame d-q axis current and corresponding phase line current

To validate the candidate machine, the rated current is fully aligned with the negative d-axis which is the most critical condition to cause demagnetization. It can be seen the magnets remain healthy in Figure 5-3 (a). If we assume a balanced stator short-circuit fault is happened and the faulty current is three times higher than the rated

value, the flux distribution on the magnet is presented in Figure 5-3 (b) and (c). It can be seen the magnet is fully demagnetized when current is aligned to the negative d-axis, while hardly any flux reverse to the magnetization direction when the current is aligned to the q-axis. Thus, it is reasonable to conclude that the magnets will not be demagnetized at any load conditions if it survives from the condition when all current is aligned to the negative d-axis.

Figure 5-3 Rotor flux density vector plot under different machine operation condition

5.3 Stator winding short-circuit current evaluation

5.3.1 Specifications of winding short-circuit condition

The demagnetization fault analysis incorporating winding short-circuit condition can be achieved by FEM modeling coupled with external circuit. In spite of the high

accuracy, the transient FEM analysis requires to re-mesh the machine at every time-step, which results in long computational time compared to magnetostatic analysis. On the other hand, only the worst scenario is valuable to assess the irreversible demagnetization of PM machines. Therefore, to improve the computation efficiency, an analytical model is used to predict the short-circuit current for the FEM analysis as shown in Figure 5-4. This single phase model is valid typically for the fault tolerant PM machine, where each of machine phases is connected with a single phase converter. This design features enhance machine's fault-tolerant capability to the stator winding short-circuit fault [57, 115].

Figure 5-4 Diagram of partial winding short-circuit fault

The relation between the faulty and healthy coil of stator winding can be represented by:

$$V_1 = R_h I_1 + L_h \frac{dI_1}{dt} + L_m \frac{dI_s}{dt} + e_1 \quad (5.1)$$

$$V_2 = R_s I_s + L_s \frac{dI_s}{dt} + L_m \frac{dI_1}{dt} + e_2 \quad (5.2)$$

where V_1 is phase terminal voltage, e_1 is the EMF induced in the healthy coil, R_h is the healthy coil resistance, I_h is the current flow through healthy coil, L_h is the

healthy coil self-inductance, L_m is the mutual inductance between healthy and faulty turns, I_s is the current of faulty coil, V_2 is faulty coil terminal voltage, e_2 is the EMF induced in faulty coil, R_s is the faulty coil resistance, L_s is the faulty coil self-inductance.

5.3.2 Slot leakage flux and inductance estimation

In order to evaluate the short-circuit current, the problem is actually transferred to evaluate the resistance and inductance of both healthy and faulty coil, as stator terminal voltage is supplied. Winding resistance is determined according to the corresponding length and size of conductor as given by:

$$R = \rho \frac{L}{A} \quad (5.3)$$

where ρ is the resistivity of copper, L is the total length of the coil, A is the cross-sectional area of the conductor.

Figure 5-5 is a schematic diagram of leakage flux distribution in the slot, where Φ_1 represents the flux associated with the short-circuit turns N_s , Φ_{2-1} and Φ_{2-2} are the flux associated with upper part and lower part of healthy turns N_a and N_b , respectively, Φ_3 is the flux associated with slot wedge and opening, Φ_r is the flux associated with airgap. Winding inductance is determined by quantifying the associated leakage flux linking the related healthy and faulty turns [116].

Figure 5-5 Slot geometrical dimensions and leakage flux component

In the following calculation, since flux induced by faulty and healthy coils need to be quantified independently, the flux linkage components shown in the above figure will be redefined. For example, Φ_3 here generally represents the flux pass through wedge opening, but the flux can be either induced by the healthy coil or the faulty coil. Hence, for the flux component induced by faulty coil, Φ_3 is redefined as Φ_{x-xo} , which can be estimated according to the permeance of slot opening area and the faulty coil MMF as given by:

$$\Phi_{x-so} = N_s^2 I_s (P_w + P_o) \quad (5.4)$$

$$P_w = \mu_0 l \frac{\tan \alpha}{2} \ln\left(\frac{W_s}{b_0}\right) \quad (5.5)$$

$$P_o = \frac{h_t - b_0 \tan \alpha}{W_s} \quad (5.6)$$

where P_w and P_o are the permeance of slot wedge and opening, respectively; l is the effective length of stator lamination; W_s is slot width; b_o is the wedge extra length compared to slot; α is the wedge angle; h_t is the total height of wedge and opening, μ_0 is the permeability of slot wedge which equals to the permeability of free space.

For the flux linking to the winding bars, it is easier to take the integration of the average flux density over the corresponding area. According to the Ampere's law, this average flux density is obtained by equation:

$$B = \mu_0 H = \mu_0 \frac{NI}{W_s} \quad (5.7)$$

where H is the flux intensity, N is the number of turns contributed to corresponding flux, I is the current flow through winding coil.

Therefore, the flux associated with the corresponding coil can be calculated by:

$$d\Phi = NBdA = \mu_0 l \frac{N^2 I}{W_s} dx \quad (5.8)$$

where the corresponding number of healthy turns and faulty turns can be counted as:

$$N_h = \frac{N(h_s + h_a - h_b)}{h_s} \quad (5.9)$$

$$N_s = \frac{N(x - h_a)}{h_s} \quad (5.10)$$

Substituting equation (5.9) and (5.10) into equation (5.8), the flux links to the faulty coil between height h_b and h_a can be represented as:

$$\Phi_{x-1} = \int_{h_a}^{h_b} \mu_0 I_s \left(\frac{N}{h_s} \right)^2 \left[\frac{(x-h_a)^2}{W_s} \right] dx \quad (5.11)$$

Similarly, the flux links to the healthy coil between h_s and h_b is calculated from the permeance of rectangular area as given by:

$$\Phi_{x-2} = \mu_0 l \frac{h_s - h_b}{W_s} N_s^2 I_s \quad (5.12)$$

By adding up the above leakage flux components together, the total leakage flux linkage of faulty turns equals to:

$$\Phi_s = \Phi_{x-so} + \Phi_{x-1} + \Phi_{x-2} \quad (5.13)$$

Similarly, the slot leakage flux links to the healthy coil can be quantified and its expression is given by:

$$\Phi_h = \Phi_{y-so} + \Phi_{y-1} + \Phi_{y-2} \quad (5.14)$$

where the corresponding flux components are:

$$\Phi_{y-so} = N_h^2 I_h (P_w + P_o)$$

$$\begin{aligned}
 \Phi_{y-1} &= \int_0^{h_a} \mu_0 I_h \left(\frac{N}{h_s} \right)^2 \left(\frac{x^2}{W_s} \right) dx \\
 \Phi_{y-2} &= P_{(h_s-h_b)} (N_a + N_b)^2 I_h \\
 &= P_{(h_s-h_b)} N_a^2 I_h + P_{(h_s-h_b)} N_a N_b I_h + P_{(h_s-h_b)} N_b^2 I_h \\
 &= \mu_0 l \frac{(h_s - h_b)}{W_s} N_a^2 I_h^2 + \int_{h_b}^{h_s} \mu_0 I_h \left(\frac{N}{h_s} \right)^2 \left[\frac{(x - h_b)^3}{3W_s} \right] dx \\
 &\quad + \int_{h_b}^{h_s} \mu_0 I_h \left(\frac{2NN_a}{h_s} \right) \left[\frac{(x - h_b)^2}{2W_s} \right] dx
 \end{aligned}$$

Likewise, the total leakage flux linking both healthy and shorted coil is given by:

$$\Phi_m = (P_w + P_0) N_h N_s I + \mu_0 l \frac{(h_s - h_b)}{W_s} N_a N_s I + \Phi_{z-1} + \Phi_{z-2} \quad (5.15)$$

where

$$\Phi_{z-1} = \int_{h_a}^{h_b} \mu_0 I \left(\frac{NN_a}{h_s} \right) \left[\frac{(x - h_a)}{W_s} \right] dx$$

$$\Phi_{z-2} = \int_{h_b}^{h_s} \mu_0 I \left(\frac{NN_s}{h_s} \right) \left[\frac{(x - h_b)}{W_s} \right] dx$$

The flux pass through airgap will be linked to both healthy and faulty turns. It can be evaluated from the airgap permeance as given by:

$$P_r = \frac{\mu_0 l \theta}{\ln(1 + (\frac{l_g}{r}))} \quad (5.16)$$

where θ is the slot pitch angle; l_g is the airgap length; and r is the rotor radius.

Since all the slot leakage flux components are obtained, the corresponding self- and mutual- inductances under faulty condition can be represented by:

$$L_s = P_r N_s^2 + \frac{\Phi_s}{I} \quad (5.17)$$

$$L_h = P_r N_h^2 + \frac{\Phi_h}{I} \quad (5.18)$$

$$L_m = P_r N_s N_h + \frac{\Phi_m}{I} \quad (5.19)$$

The transient current performance of both healthy and faulty coil can be predicted according to the current and voltage relation:

$$\begin{bmatrix} \frac{dI_1}{dt} \\ \frac{dI_s}{dt} \end{bmatrix} = \begin{bmatrix} L_h & L_m \\ L_m & L_s \end{bmatrix}^{-1} \begin{bmatrix} V_1 - R_h I_1 - e_1 \\ V_2 - R_s I_s - e_2 \end{bmatrix} \quad (5.20)$$

Under the short-circuit condition, voltage V_2 is nil, and the back-EMF can be calculated by the classical equation:

$$e = \sqrt{2}\pi f N \Phi_{air} \quad (5.21)$$

where f is the rotation frequency; N is the number of turns; Φ_{air} is the airgap flux linkage.

5.4 Result and analysis

For demagnetization fault assessment, commercial software JMAG Designer is used to conduct both magnetostatic and transient FEM analysis, and MATLAB/Simulink is used for basic calculation and to evaluate the short-circuit current predicted by analytical model. Computation time counted for conventional and proposed approaches are based on the same computer embedded with Intel Core i7 CPU and 8GB RAM.

5.4.1 Short-circuit current prediction by analytical model

In transient FEM analysis, the candidate machine model is connected to the external circuit with controllable switches to simulate short-circuit condition. Figure 5-6 presents the current when the sixth winding turn counted from innermost position is shorted under rated machine operation condition. The manipulated short-circuit fault is incepted at 0.2 second where the short-circuit current is more than four times higher than the rated current at steady-state condition. In this case, the analytical model presents good agreement with FEM analysis though a certain deviation during transient time can be observed.

Figure 5-7 shows the peak current of single turn short-circuit from the innermost to the outermost slot position. It can be seen that the current evaluated by FEM analysis exhibits significant deviation compared to the current predicted by analytical model for short-circuit turn in the front position and rear position. This is due to the uneven flux distribution and leakage flux in the tooth tip area where the magnetic flux density is higher than the flux density in the rear area.

Figure 5-6 Transient current obtained by FEM analysis and analytical method for the 6th turn short-circuit

Figure 5-7 Peak current of single turn short-circuit condition for different fault locations

The FEM analysis is able to capture global directions of flux passage, whereas the analytical model excludes fringe and tooth-to-tooth flux which degrade the model accuracy. The maximum deviation of the faulty current predicted by analytical model is 1872A at the innermost coil position. It is equivalent to percentage error less than 13% compared to FEM analysis. For demagnetization fault assessment, the high deviation in these lower current cases will not affect the assessment result, because machine should be designed to tolerant the peak short-circuit current for all of fault locations.

Figure 5-8 Peak current of various number of shorted turns

The analytical model is also used to predict the faulty current due to multiple number of short-circuit turns, as shown in in Figure 5-8. From the results, the short-circuit current predicted by analytical model is more close to the ones obtained by FEM analysis when the number of faulty turns is less than four. The biggest deviation between analytical model and FEM analysis is happened for six turns short-circuit which is equivalent to 6.5% percentage error. The presented short-circuit currents

are the peak values obtained among all of the possible locations in the slot, where the shorted turns are assumed to be sandwiched by healthy turns. Even though the occasions that healthy turns are sandwiched by shorted turns are possibly existing, it is rarely happened since the area close to faulty turns are firstly affected. Also, the occasions that two or more separate short-circuit faults happens simultaneously in the stator are not considered.

5.4.2 Demagnetization fault assessment under partial-turn winding short-circuit

In order to assess the demagnetization fault, it is better to clarify the difference between reversible and irreversible demagnetization which can be illustrated by Figure 5-9. Under the healthy operating, magnet undergoes reversible demagnetization as the operating point moves along the identified portion above the knee point of the B-H curve. Magnet will be subjected to irreversible demagnetization if the operating point is forced to move below this knee point. For this circumstance, the operating point of magnet is no longer able to move backwards to the designed operation portion of the curve. Instead, it will follow a recoil curve which has lower remanence but the same slope to the original curve after the magnetic field intensity is relaxed.

Six identification points are chosen near the magnet front edge to monitor the flux density over the magnet, as shown in Figure 5-10. These points on the magnets are next to the rotor front area, where has the highest magnetic field gradient on the rotor. Points A, C, D, and F are located at the corners of magnets and near the magnet pocket, because they can be demagnetized most easily, while points B and E are

comparably less critical [117]. As a result, the magnets are irreversible demagnetized if the flux density of any of these points is below the knee points of B-H curve.

Figure 5-9 Magnetization curve for NdFeB magnet at 110 °C operation condition

The operation temperature of rotor magnet is set to 110°C which is an ordinary safe operating temperature for electrical machines. When the temperature increases, the magnitude of B_r and H_c will become smaller and move the curve towards the origin, which makes the magnet prone to be more easily demagnetized. However, the investigation of real temperature effect requires the fluid dynamic analysis and machine cooling may also be included, which is not considered in this study. Stator winding current is configured to be aligned with d-axis only which is equivalent to the most critical condition to demagnetize the magnet among the entire machine operating points.

Figure 5-10 Demagnetization identification points on the magnet

Figure 5-11 Critical machine operating points to demagnetization

When the machine is operated under fault-tolerant mode, the strength of the opposite magnetic field is determined by the number of shorted turns and the corresponding short-circuit current. Fault is incepted to the phase with the highest current which is corresponding to the worst short-circuit condition that provokes demagnetization. The operating points of d-axis current are configured from 2 kA to 7 kA in a rising step of 1 kA, except for the 6 kA operating point which is replaced by the rated

operating point. These critical operating conditions are indicated by yellow dots on machine operation curve as shown in Figure 5-11.

Figure 5-12 Flux density aligned to the magnet demagnetization identification points for various number of shorted turns at $I_q=0A$, (a) one turn shorted (b) two turns turn shorted (c) three turns shorted (d) four turns shorted.

A horizontal threshold line is placed in the plot to identify the boundary of irreversible demagnetization. This line is equivalent to the knee point of the magnet's B-H curve. Flux density at any points lower than this threshold indicates that irreversible demagnetization occurs. In the case of ideal control strategy, the winding current is regulated to be fully aligned with the d-axis. The corresponding flux density over the six identification points is shown in Figure 5-12 and Figure 5-13.

Figure 5-13 Flux density aligned to the magnet demagnetization identification points for various number of shorted turns at $I_q=0$, (e) five turns shorted (f) six turns shorted (g) seven turns shorted (h) eight turns shorted.

In the figures, the flux density over the magnet monotonically decreases as the amplitude of negative d-axis current increases. For one and two turns short-circuit condition, as shown in (a) and (b), flux density of all the identification points are above the threshold line for any machine operating conditions. Identification points C and D are located at the position far away from the center of two magnet cavities where the magnetic flux concentrates. They have the lowest flux density for all the cases. It can be found in (c), when three turns are shorted, identification points C and D are subjected to irreversible demagnetization under machine rated operating

condition. The rest of identification points remain healthy even under overrated operating points. The four turns short-circuit situation is critical as points A, B, E, F are very close to the knee point at rated operating condition as shown in (d).

Figure 5-14 Flux density aligned to the magnet demagnetization identification points for various number of shorted turns at $I_q=500\text{A}$, (a) one turn shorted (b) two turns turn shorted (c) three turns shorted (d) four turns shorted.

If five turns short-circuit happens, two magnets will be fully demagnetized under the rated operating condition as seen in (e). The remediation to the stator winding may not be sufficient to protect the machine by only regulating the current to the rated value. Instead, the d-axis current must be regulated below rated operating point in order to prevent magnet from irreversible demagnetization. If more than 50% of

the turns are shorted, as given by (f)-(h), the magnet will be irreversible demagnetized when d-axis current equals to 5 kA. Machine safe operating current can be found according to the presented analysis. For instance, during fault-tolerant operation, it will effectively avoid demagnetization if negative d-axis current can be controlled lower than 3 kA even 80% of winding turns are subjected to short-circuit.

Figure 5-15 Flux density aligned to the magnet demagnetization identification points for various number of shorted turns at $I_q=500\text{A}$, (e) five turns shorted (f) six turns shorted (g) seven turns shorted (h) eight turns shorted.

The influence of cross-coupling effect to the irreversible demagnetization is examined by aligning 500A current to the q-axis. The flux density over the six identification points is shown in Figure 5-14 and Figure 5-15. Ideally, the q-axis

winding current will not affect d-axis magnetic flux since machines are magnetically isolated between the two axes. However, cross-coupling effect always exists since machines cannot be perfectly manufactured. Compared to the analysis without q-axis current excitation, it can be seen in case (a) and (b) that the flux density on the magnet identification points decreases further. Identification points C and D near rotor rib exhibit the lowest flux density. Differently, the demagnetization fault can be found in (b) in the presence of q-axis flux.

The cross-coupling due to q-axis current also offset the rotor magnetization flux. The offset effect is not significant when stator winding current is low. As shown in (c) and (d), when the number of short-circuit turns is large, d-axis magnetic dominates the opposite magnetic field which exhibits the weakened influence of cross-coupling. On the other hand, it also can be found in (e) to (h) where the flux density of identification points is almost the same with the ones without q-axis current excitation, because this effect is mitigated by the d-axis magnetic field and its influence becomes very insignificant to the irreversible demagnetization.

5.4.3 Time required by using transient FEM analysis and FEM analysis incorporating analytical model

The elapsed time required for transient FEM analysis and static FEM analysis incorporating analytical model is given in Table 5-1. The time required to obtain the short-circuit current is less than one second by using analytical model, while the elapsed time for transient time FEM analysis is 135 times longer than static FEM analysis. It is possible to further reduce the time required for transient FEM analysis by optimizing the meshing settings of FEM. However, the improvement will still be

insignificant compared to the much less time required of static FEM analysis. The comparison of time required is recorded for only one turn short-circuit fault at the rated operating condition. Much more time will be saved for the designers who try to find the optimal design from various fault-tolerant operations.

Table 5-1 Time required by two different analysis approaches

	Transient FEM analysis	Static FEM analysis
Number of elements	15634	15487
Steps	120	N/A
Elapsed time	1620 seconds	12 seconds

5.5 Summary

The risk assessment of irreversible demagnetization can be achieved by time-stepping transient FEM analysis with high degree of accuracy. However, this approach is hardly used as a convenient tool to continuously assess the demagnetization risk due to the long computation time required. The presented study introduces an analytical model incorporating static FEM analysis which estimate the short-circuit current by quantifying the flux link to the healthy and the faulty coils. A wide range of machine operating points which are risky to the magnet have been assessed by using the proposed approach, and the computation efficiency has been significantly improved compared to the conventional approach. This novel approach can be effectively used for machine and fault mitigation control designers to improve their candidate design and reduce the risk to cause irreversible demagnetization. Also,

with the help of highly efficient computation, a database can be prepared for various machine operation points, which may be used as a guideline to regulate the machine to work within safe operation range. However, the flux quantification method may be inapplicable for the machines with large number of turns. Future works are necessary in order to extend this risk assessment approach to other types of PM machine.

CHAPTER 6 MACHINE AIRGAP ECCENTRICITY FAULT DETECTION BY USING SEARCH COIL

6.1 Introduction

Airgap eccentricity fault can happen to all types of radial flux electrical machines, which is caused by various reasons, including bearing failure, irreversible demagnetization, load imbalance, or imperfect manufacturing such as core ovality and misalignment of rotor shaft. So far, there are plenty of techniques which have been proposed to detect this fault, as aforementioned in chapter 2.4. Although some of them have been implemented for industry applications, such as MSCA and stray flux, it is a matter of fact that the majority of electrical machines are out of monitoring, because of the high cost and most technologies are machine-dependent [90, 118]. Therefore, the investigation of cost-effective method which is adaptable to different types of machine is still necessary.

In this chapter, a simple dual-search coils method has been proposed, based on the idea that the eccentric airgap would cause asymmetric magnetic field distribution over symmetric machine poles. This method employs low cost search coils which are placed in both machine airgap main flux and stray flux. It is easy to implement and dedicated to indicate machine operating abnormality. In order to justify the machine independency of this method, both interior PM machine and squirrel cage induction machine (IM) are used as the candidate machine in this study.

6.2 Modeling of machine airgap eccentricity

6.2.1 Candidate interior PM machine and squirrel cage induction machine

Figure 6-1 shows the layout of both machines implemented with dual search coils, where (a) is the 2.2MW interior PM machine used in the previous chapter, (b) is the new introduced squirrel cage induction machine. The internal search coils are wound at tooth tip to gauge airgap main flux and the external search coils are placed close to the machine outer surface to gauge the leakage stray flux. Both internal and external search coils contain two sets of coils, which are placed 180 degree from each other. The coils placed near machine vicinity have ten turns per coil, whereas only one turn coil is used for the inner coil to minimize the invasive modification of airgap. The specifications of the new squirrel cage IM is presented in Table 6-1.

Figure 6-1 Candidate machine with dual search coils (a) interior PM machine, (b) squirrel cage IM

Table 6-1 Specifications of the candidate IM

Parameters	Value
Power	250 [kW]
Rated voltage	2.8 [kV]
Frequency	20 [Hz]
Airgap length	1.7 [mm]
Turns	100 turn/phase/pole
Cage material	Aluminium
Shaft	Non-magnetic material

6.2.2 Characterization of airgap eccentricity

Airgap eccentricity can be characterized according to the displacement between rotor, stator, and rotor rotation symmetrical axis as shown in Figure 6-2. The center of stator and rotor symmetrical axes are represented by a hollow dot, and the rotor rotation center is represented by a solid dot, which are coincided with each other for healthy machine condition as shown in (a). The rotor center is coincided with rotation center, but it is displaced with respect to the stator center for static eccentricity (SE) condition as shown in (b). For dynamic eccentricity (DE) as shown in (c), the stator center is coincided with rotation center but displaced with respect to rotor center. When SE and DE happens simultaneously, stator center, rotor center, and rotation center are all displaced with respect to each other, which is the mixed eccentricity (ME) condition as shown in (d).

Taking into account rotor motion, the length of airgap remains unchanged under SE condition although the rotor is off-centered. On the other hand, the length of airgap

is time-dependent for DE and ME conditions, which means that the airgap length depends on the relative rotor and stator positions [119]. Figure 6-3 shows a coordinate axis which can be used to calculate the actual length of airgap. The origin of this coordinate is the stator symmetric center as indicated by point A. Point B and point C are the rotor symmetric center and rotation center, respectively.

Figure 6-2 Positions of rotor, stator, and rotation center in (a) healthy condition, (b) static eccentricity, (c) dynamic eccentricity, (d) mixed eccentricity.

Figure 6-3 Position of stator center, rotor center and rotation center of mixed eccentricity condition

To determine the airgap length, the x-axis of this coordinate is set to be aligned with vector $\vec{AC}$ so that the center of SE is a fixed point. The length of vector $\vec{AC}$ determines the magnitude of SE condition which is off-centered from the stator symmetric axes. Similarly, the length of vector $\vec{CB}$ determines the magnitude of DE condition, and the summation of vector $\vec{AC}$ and $\vec{CB}$ is the vector $\vec{AB}$ which determines the ME condition. Their relations can be represented by equation:

$$|\vec{AB}| = \sqrt{|\vec{AC}|^2 + |\vec{CB}|^2 + 2|\vec{AC}||\vec{CB}|\cos\theta} \quad (6.1)$$

where θ is the angle of vector $\vec{CB}$ which is dependent of rotor positions.

The angle of vector $\vec{AB}$ can be determined by equation:

$$\alpha = \tan^{-1} \frac{\sin\theta|\vec{CB}|}{|\vec{AC}| + \cos\theta|\vec{CB}|} \quad (6.2)$$

Assuming point E is on the rotor outer circumference, $|\vec{OB}|$ is the height of triangle

AEB, the corresponding length of vector $\vec{AE}$ can be calculated as:

$$\vec{AE} = \vec{AO} + \vec{EO} = |\vec{AB}|\cos(\beta - \alpha) + \sqrt{R_r^2 - \sin^2(\beta - \alpha)}|\vec{AB}| \quad (6.3)$$

where R_r is the rotor radius, β is the angle of vector $\vec{AE}$.

Representing machine inner stator radius by R_s , the radial length of airgap at corresponding angle β is given by:

$$g(\beta) = R_s - |\vec{AE}| \quad (6.4)$$

The severity of rotor eccentricity is usually defined by eccentricity factor μ , which is the ratio of rotor eccentricity length and symmetrical airgap length. Due to the imperfection of manufacturing, the eccentricity factor smaller than 10% is usually acceptable [4, 120].

6.2.3 FEM modeling of airgap eccentricity fault

In this study, the commercial FEM package JMAG Designer 12.1 is used to create the required eccentricity fault conditions, due to the difficulties to physically move the real machine rotor. Since both of the candidate machines are not skewed, only two-dimensional transient analysis is used to simulate airgap eccentricity. An air space which is 1.5 times the stator outer radius is created as the analysis domain for FEM analysis, in order to capture the leakage stray flux out of machine vicinity. The machine is connected to constant load and three phase current source to simulate the steady-state condition.

Machine healthy condition along with static-, dynamic-, and mixed-eccentricity fault condition for the IM are configured as shown in Figure 6-4. The eccentricity of rotation center and rotor symmetric center is set to 0.425 mm, which is corresponding to 25% eccentricity towards positive x-axis for the SE and DE conditions as

given in (b) and (c), respectively. The eccentricity factor is set to 52% for ME condition as shown in (d), where the rotor symmetric center is moved to the point (0.425 mm, 0.2 mm) and rotation symmetric center is moved to the point (0.2 mm, 0.425 mm). The same eccentric airgap conditions are applied to the interior PM machine, which is not presented due to its similarity.

Figure 6-4 2D FEM model for (a) Healthy condition, (b) 25% static eccentricity, (c) 25% dynamic eccentricity, (d) 52% mixed eccentricity.

6.3 Result and analysis

The induced voltage of search coils for healthy, SE, DE, and ME conditions are presented in this section. Since the magnetic field distribution is symmetrical, search coil located 180° away from each other should have the same induced voltage under healthy operating condition. Due to airgap irregularity, the induced voltages at the

two symmetric coils are no longer the same. Here, the induced voltage for different airgap eccentricity conditions for both machines are presented, and also the information richness contained in the main flux and stray flux are compared to investigate their potentials of detect eccentricity fault detection.

In the case of airgap eccentricity, the variation of airgap magnetic field will induce additional frequency components in the airgap. The magnitude of additional frequency depends on the eccentricity degree, slot opening, load condition, and magnetic saturation. For the IM, the mathematical expression of airgap additional harmonics is given by [121]:

$$f_e = f_s \left[(kR \pm n_d) \left(\frac{1-s}{P} \right) \pm n_{ws} \right], \quad k=1,2,3... \quad (6.5)$$

where f_s is supply frequency, R is the number of rotor slots, n_d is 1 if dynamic eccentricity presents, s is machine slip, P is number of pole pairs, n_{ws} equals to 1,3,5...

As the rotor rotates at synchronous speed for the PM machine, the additional airgap frequency components is given in the form:

$$f_e = \left(1 \pm \frac{k}{P} \right) f_s \quad k = 1, 2, 3... \quad (6.6)$$

These additional frequency components will give rise to the existing frequency components of airgap field. In terms of the actual phenomenon, the higher order frequency components coincide with machine natural frequency can cause machine to resonate and result in vibration. Also, the higher order frequency components can

result in higher core losses which create increased loss heating and it can shorten the life of machine. Moreover, the additional frequency components can result in fluctuation of machine torque, which is determined by the radial and tangential components of airgap magnetic field [122].

6.3.1 Search coil voltage induced by airgap main flux

Search coil wounded at tooth tip is used to gauge airgap flux, in other words the main flux as it generates machine power, where the induced voltage exhibits the same fundamental frequency of stator current as shown in Figure 6-5 and Figure 6-6. Compared to the healthy condition, it can be seen that the induced voltage of two search coils contains significant deviation under faulty conditions for both machines. In order to recognize the difference, the FFT is applied to the voltage signals and the spectrum up to 10 times of fundamental frequency is presented.

Figure 6-5 Search coil voltages induced by airgap main flux for IM under healthy and eccentricity conditions

Figure 6-6 Search coil voltages induced by airgap main flux for PM machine under healthy and eccentricity conditions

Figure 6-7 Harmonics of the induced voltage of internal search coils for IM under healthy condition

Under healthy operating condition, as given in Figure 6-7 and Figure 6-8, it can be seen that the spectrum of voltage induced by two coils are almost identical, so the primary assumption of symmetric magnetic field holds for both IM and interior PM machine. For the SE condition, as shown in Figure 6-9 and Figure 6-10, the magnitude of fundamental frequency component of two coils exhibits deviation about 5.5%

for the IM and 2.3% for PM machine. This is due to the higher flux level caused by smaller airgap length as rotor eccentric towards the search coil wounded at 30° for the IM.

Figure 6-8 Harmonics of the induced voltage of internal search coils for PM machine under healthy condition

Figure 6-9 Harmonics of the induced voltage of internal search coils for IM under static eccentricity condition

Figure 6-11 and Figure 6-12 shows the voltage spectrum due to DE, where the magnitudes of fundamental frequency component for search coil voltages are almost the same for both IM and PM machine, due to the identical effective airgap length in the symmetrical position. The small difference in the magnitude is due to the numerical error of FEM analysis. Compared to the healthy condition, the magnitude of fundamental component is reduced by 6.8% and 9.1% for IM and PM machine, as the signature of machine operating abnormality under DE.

Figure 6-10 Harmonics of the induced voltage of internal search coils for PM machine under static eccentricity condition

Under ME condition, the voltage difference between the two coils is just 2.5% for IM, due to the small difference of airgap length at the two positions. However, the reduction of magnitude compared to healthy condition is still valid to identify operating abnormality. For the PM machine, as shown in Figure 6-14, the magnitude of fundamental voltage component reduced by 3.4% and 9.2% for the search coil located at 15° and 195°, respectively. It is due to the relative higher flux as rotor eccentric towards the 15° position, similar to the situation under SE condition.

Figure 6-11 Harmonics of the induced voltage of internal search coils for IM under dynamic eccentricity condition

Figure 6-12 Harmonics of the induced voltage of internal search coils for PM machine under dynamic eccentricity condition

From this study, it can be seen that the airgap main flux is a promising indicator for airgap eccentricity fault detection, as only the fundamental voltage component of search coil is required and it is not necessary to apply complicated transforms and spectrum analysis. The employment of two search coils provides more information

to identify the specific type of eccentricity, which is hardly achieved by using only one coil.

Figure 6-13 Harmonics of the induced voltage of internal search coils for IM under mixed eccentricity condition

Figure 6-14 Harmonics of the induced voltage of internal search coils for PM machine under mixed eccentricity condition

6.3.2 Search coil voltage induced by stray flux

In the ideal situation when there is no saturation and machine components do not attenuate flux, the stray magnetic field exhibits the similar character of airgap magnetic field. However, in reality, machine stator back yoke is designed as small as possible in order to reduce machine weight and size, so saturation does affect the stray flux [123]. Moreover, the attenuation effect due to machine stator and frame also significantly influence the stray flux. It has been pointed that the predominant frequency components in the external radial field are not necessarily predominant components in the airgap [124]. Compared to airgap main flux, the stray flux is essentially very weak as it is mainly contributed by the flux leaked from stator yoke in the radial direction. However, it is much easier to capture than airgap main flux, because external search coils are placed outside machine. It is completely non-invasive to the machine and also easy to install. In this case, similar to the internal coils, the two search coils are placed at symmetrical magnetic field position close to the stator yoke.

Figure 6-15 Terminal voltage of stray flux search coil for IM under healthy and eccentricity conditions

Figure 6-16 Terminal voltage of stray flux search coil for PM machine under healthy and eccentricity conditions

As shown in Figure 6-15 and Figure 6-16, the induced voltage is much noisy compared to the voltage induced at internal search coil. By applying the FFT, the voltage spectrum for IM and PM machine under healthy condition is respectively given in Figure 6-17 and Figure 6-18, where the frequency components up to ten times of fundamental frequency is presented. As expected, the magnitude of these frequency components is identical measured by the two search coils placed at symmetrical positions for both the IM and the interior PM machine.

For the SE condition, the variation of voltage spectrum components exhibits significant difference for the IM, as shown in Figure 6-19. The magnitude of voltage 20Hz, 60Hz, and 100Hz components are reduced more than 50% compared to the healthy condition, while the magnitude of other frequency components are significantly increased. The magnitude of these 20Hz, 60Hz, and 100Hz frequency components is higher for the search coil located at 45° , as the rotor eccentric towards this direction.

Figure 6-17 Harmonics of the induced voltage of external search coils for IM under healthy condition

Figure 6-18 Harmonics of the induced voltage of external search coils for PM machine under healthy condition

For the PM machine, the differences between the voltage frequency components of the two search coils are insignificant as shown in Figure 6-20, where the deviation of 50Hz, 150Hz, and 250Hz are 1.8%, 2.5%, and 5.8% respectively. This is due to the high stator current of this large power PM machine, where the eccentric rotor magnetic field does not significantly influence the stator magnetic field. Considering the numerical error of FEM analysis, it is hard to say the SE can be detected.

Figure 6-19 Harmonics of the induced voltage of external search coils for IM under static eccentricity condition

Figure 6-20 Harmonics of the induced voltage of external search coils for PM machine under static eccentricity condition

The magnitude of 20Hz, 60Hz, and 100Hz components is also reduced in the case of DE condition for the IM, as shown in Figure 6-21. Different from SE condition, the airgap length is the same for the search coils placed at symmetrical positions, so the fundamental voltage spectrum of two search coils is almost identical. For the PM machine, as shown in Figure 6-22, the deviation between 50Hz, 150Hz, and 250Hz

voltage component is also insignificant as the case in SE, while the reduction of the magnitude compared to the healthy case is about 8%. Therefore, it can only identify the abnormal reduction of flux, while the signature due to DE condition is not significant.

Figure 6-21 Harmonics of the induced voltage of external search coils for IM under dynamic eccentricity condition

Figure 6-22 Harmonics of the induced voltage of external search coils for PM machine under dynamic eccentricity condition

For the ME condition, as shown in Figure 6-23, the magnitude of 20Hz, 60Hz, and 100Hz components of IM are higher than the cases under SE and DE conditions. Similar to SE condition, the magnitude of voltage component measured by search coil located at 45° is higher than the ones measured by search coil located at 225° . For the PM machine, as given in Figure 6-24, it can be seen that the magnitude of fundamental voltage component of coil located at 15° is 6.6% higher than the one at 195° , while the 3rd order component is 5.0% lower.

Figure 6-23 Harmonics of the induced voltage of external search coils for IM under mixed eccentricity condition

Figure 6-24 Harmonics of the induced voltage of external search coils for PM machine under mixed eccentricity condition

By comparing the voltage induced by external search coils for both machines under healthy, SE, DE, and ME conditions, it can be seen that the deviation of fundamental voltage component of external search coils is less significant than the one induced by internal search coil. In the meantime, the variation of higher order voltage components can hardly be used as indicator for this simple magnitude comparison, as they are likely dependent of machine type and its operating condition. So far, the stray flux method has been applied to IM operating at stationary condition, but it is not suitable for converter connected machines operate in non-stationary conditions. The higher 3rd order harmonic is likely due to magnetic saturation but more investigations are required [124].

6.4 Summary

This chapter presents a method by using dual search coils to detect airgap eccentricity of the radial flux electrical machine, based on the idea that the magnetic flux is symmetrically distributed between machine poles. The employed search coils are placed both inside the machine to gauge the airgap main flux and outside the stator core to gauge the stray flux. It is expected to eliminate the influence of machine type and load condition by just comparing the fundamental component of voltage induced at search coil.

From the result, it can be seen that the voltage induced by airgap main flux is significant to identify eccentric airgap. Moreover, the deviation of the voltage between the dual search coils can be used to indicate the type of eccentricity. The direction of SE can also be found by comparing the voltage of search coil placed at symmetrical positions. However, it is more suitable for machines with small number of poles,

such as the IM introduced with four poles. For the machine with big number of poles, such as the PM machine introduced with 12 poles, it is less significant to indicate eccentric direction, but this can be improved by using more coils placed at symmetrical positions.

The stray flux is much weak than airgap flux, which makes it difficult to use if only comparing the fundamental voltage component. However, the external search coils are non-invasive to the machine and it is easy to install. Hence, the external search coil based method is still a good option to detect airgap eccentricity. In the meantime, more investigations are required for the higher order spectrum components, as their signatures are more likely dependent of machine type and its operating conditions.

CHAPTER 7 CONCLUSIONS

7.1 Conclusions

This thesis presents research studies of using electromagnetic approach to analyse machine fault and to improve machine operation reliability. The main contents include machine operation characteristic prediction by using MEC model, demagnetization fault analysis of bar-wounded PM machine under short-circuit condition, and airgap eccentricity fault detection by using search coil. Although promising results have been obtained through a comprehensive study in machine faults, there are still some gaps in technology readiness level that need to be bridged in order to apply our research outcomes to industrial applications.

Specifically, a numerical model by using MEC method is proposed to predict machine performance for both healthy condition and for stator winding short-circuit condition. The model design procedure is introduced in a generalized way which is easy to follow and can be applied for different types of PM machines. Compared to the FEM analysis, the MEC model features appealing accuracy and much faster computation speed, which makes it very suitable to be used as a convenient tool to assist in developing fault mitigation techniques. Its drawback when compared with FEM is that it requires considerable experience and effort to design a successful model. Nevertheless, the MEC model can be a good alternative for the service and

maintenance sector which find the market available FEM packages to be too expensive and requiring too long computation times.

The previously-reported works mainly focused on analyzing the demagnetization faults arising from stator phase short-circuit, while the impact of inter-turn winding short-circuit has not adequately considered. Our risk assessment has shown that the inter-turn winding short-circuit of bar wounded PM machine can also result in irreversible demagnetization fault. Hence, any short-circuit mitigation of this type of machine should also account for the risk to cause demagnetization fault. Besides, the presented assessment incorporates an analytical model, which significantly reduce the time required to evaluate short-circuit current. It helps to quickly assess all of machine critical operation points, and the results can be effectively used as a guideline for fault-tolerant machine design.

Lastly, a dual search coil method is proposed to detect airgap eccentricity fault for a squirrel cage induction machine. The coils are placed at the symmetrical positions to gauge the variation of both airgap flux and stray flux, and the difference of voltage signature is used to identify the airgap condition. The results show that dual search coil method can effectively identify machine eccentric airgap and the difference of voltage fundamental component can be used to differentiate static eccentricity and dynamic eccentricity. External search coils is non-invasive to the machine interior and it is flexibly to install. However, it is less sensitive than the airgap main flux, and the stay flux may be possibly influenced by other causes, i.e. strong stator current or environmental flux.

7.2 Suggestions for future work

Upon completion of this thesis, we have obtained some technical solutions that can help to improve the machine operation reliability. However, due to the limitation of time and resources, there are still some more researches and technical problems, which can be considered for future researches. These include:

1. Online machine fault detection and operating parameter estimation using MEC model.

The presented studies have shown that the MEC model is fast and accurate in predicting machine operating parameters, which is intended for machine and its drive designers who find FEM software packages too costly and slow in computation. Nevertheless, the MEC model will be more useful if it can be implemented with a microprocessor to conduct online machine operating parameters evaluation. Also, it is necessary to couple with external circuit, such as winding, grid or power converters. If so, the evaluated parameters can be compared with actual parameters to detect machine operating anomalies regardless the load conditions. Also, the real-time parameters can be used to improve machine drives and control to achieve higher dynamic machine performance. However, it would require the MEC model to have even faster computation speed, which is a challenging problem as the model accuracy may be balanced out.

2. Using dual search coil method for electrical machine fault detection and failure prognosis.

This thesis introduces the basic idea of using dual search coils to detect the machine airgap eccentricity fault, where the machine is assumed to be perfectly manufactured.

However, in reality, machine manufacturing is always imperfect and the flux distribution may be asymmetric in nature. Thus, the analysis taking into account inherent eccentric airgap is important to further employ dual search coils in solving practical problems. Besides, it is necessary to investigate the effectiveness of using dual search coils to detect other types of machine faults, such as stator winding short-circuit fault, demagnetization fault, and broken rotor bar fault. More importantly, the voltage signatures induced by search coils should be characterized for different machine operation anomalies, so they can be used to identify the fault type. These signatures may also provide the information of fault severity which can be used to develop the techniques for machine failure prognosis.

3. Experiment validation of the dual search coil method for machine fault detection.

The FEM analysis has been found to provide high flexibility and accuracy in analyzing electrical machine fault. However, there is still a gap between the numerical modeling and real machine performance. For future works, although it is very difficult to precisely control the length of eccentric airgap, the experiment is preferred to validate the proposed dual search coil method for machine fault detection. Hence, the stray flux induced by external circuit and manufacturing defect, which are ignored by the FEM analysis, can be accounted in the research work.

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