Faculty of Electrical Engineering

INFLUENCE OF NON-UNIFORM NUMBER OF TURNS PER COIL AND STATOR GEOMETRY ON UNBALANCED MAGNETIC FORCE IN BRUSHLESS PERMANENT MAGNET MACHINE

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DECLARATION

I declare that this thesis entitled “Influence Of Non-Uniform Number Of Turn Per Coil And Stator Geometry On Unbalanced Magnetic Force In Brushless Permanent Magnet Machine ” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

Signature : ……….……………………………………………

Name : SYED MUHAMAMMAD BIN S ABDULLAH AL HABSHI

Date :……………………………………………………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature :……………………………………………….

Supervisor name : DR. MOHD LUQMAN BIN MOHD JAMIL

Date :………………………………………………..

DEDICATION

To my beloved family

ABSTRACT

The Three Phase Permanent Magnet Brushless machines in which slot number and pole number combinations are similar such as differ by one have to be configured with asymmetric winding pattern in order to obtained perfect balanced back-emf among phases. However, the asymmetric winding pattern inherently results an unwanted force which is commonly known as an Unbalanced Magnetic Force or Unbalanced Magnetic Pull. An acoustic noise and vibration are the end results of this phenomenon. In some robotic application systems that require an accurate positioning control, this phenomenon is sometimes considerably severe. Investigations of electromagnetic performance in the asymmetric winding permanent magnet machines are carried out by using 2-D Finite-Element Analysis and the developed prototype machines are tested for verification purpose. In principle, the investigations are mainly driven by the efforts of minimizing the Unbalanced Magnetic Force. In this research, a reduction of Unbalanced Magnetic Force is achieved by implementing two approaches, i) non-uniform number of turns per coils in every tooth in a respective phase, and ii) an asymmetric design of stator. The investigation shows that only the first implementation technique is successful as reducing the existing Unbalanced Magnetic Force by 18% without damaging the desired torque performance in the subjected machines. Although the second implementation technique also could reduce the Unbalanced Magnetic Force, severe degradation of the torque performance as well as a bigger cogging torque existed. It is also shown that that the Unbalanced Magnetic Force is mostly influenced by it radial component instead of the tangential component. A reduction of radial force component result in a smaller Unbalanced Magnetic Force globally. Practically, the optimized design of machine is recommended for industrial applications which requires accurate position control such as robotic arm and conveying system.

ABSTRAK

Mesin Tiga Fasa, Bermagnet Tetap Tanpa Berus yang mempunyai kombinasi jumlah slot and jumlah kutub yang hampir sama seperti dibezakan oleh nilai satu perlu mempunyai susunan seluruh corak lilitan tidak simetri bagi menghasilkan voltan teraruh yang sempurna pada semua fasa. Walaubagaimanapun, corak lilitan tidak simetri menyebabkan kewujudan daya yang tidak diperlukan yang biasanya dikenali sebagai Daya Magnet Tidak Seimbang atau Tolakan Magnet Tidak Seimbang. Satu bunyi akustik dan getaran terhasil akibat dari fenomena diatas. Dalam beberapa sistem aplikasi robotik yang memerlukan ketepatan kawalan kedudukan, fenomena ini kadangkala memudaratkan. Penyiasatan-penyiasatan keatas gerak laku elektromagnet bagi mesin-mesin yang mempunyai susunan seluruh corak lilitan tidak simetri dilakukan menggunakan Analisis Finite-Element dan prototaip-prototaip mesin yang dibangunkan diuji bagi tujuan penegesahan. Secara prinsip, penyiasatan-penyiasatan yang dilakukan adalah berpandukan kepada usaha-usaha mengurangkan Daya Magnet Tidak Seimbang. Dalam penyelidikan ini, pengurangan Daya Magnet Tidak Seimbang dicapai dengan melakukan dua pendekatan, i) penggunaan jumlah lilitan yang tidak seragam pada setiap gegelung koil dalam satu fasa dan ii) menghasilkan rekabentuk pemegun yang tidak simetri. Penyiasatan yang telah dilakukan menunjukkan hanya pendekatan penyiasatan yang pertama berjaya mengurangkan Daya Magnet Tidak Seimbang tersebut sebanyak 18% tanpa merosakkan daya putaran yang diusahakan dalam mesin-mesin yang terlibat. Walaupun pendekatan yang kedua boleh mengurangkan Daya Magnet Tidak Seimbang, pengurangan ketara keatas gerak laku daya putaran dan kewujudan daya rangkakan yang besar terhasil. Kelihatan juga bahawa Daya Magnet Tidak Seimbang amat dipengaruhi oleh komponen jejarian daya berbanding komponen tangen yang sedia ada. Pengurangan komponen jejarian daya tidak seimbang menghasilkan pengurangan Daya Magnet Tidak Seimbang secara amnya. Secara praktis, recabentuk mesin yang dihasilkan amat sesuai bagi aplikasi industri yang memerlukan kejituan kawalan kedudukan seperti sistem tangan robot dan sistem penghantaran.

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LIST OF ABBREVIATIONS

ABBREVIATION	DETAILS
AFIR	Axial Field Internal Rotor
BLDCPM	Brushless DC PM Motor
CPSR	Constant Power Speed Range
EMF	Electromotive Force
FEA	Finite-Element Analysis
GCD	Greater Common Deviser
IPM	Interior Permanent Magnet
LCM	Least Common Multiple
PM	Permanent Magnet
RPM	Revolution Per Minute
SPM	Surface Mounted Permanent Magnet
TRV	Torque to Rotor Volume
TORUS	Double Rotor Single Stator
UMF	Unbalanced Magnetic Force

LIST OF PUBLICATIONS

1. M.L.M. Jamil, **S.M.S.A. Al-Habshi**, M.N. Othman and T. Sutikno, "Performance of Fractional-Slot Winding PM Machines due to Un-even Coil Turns and Asymmetric Design of Stator Teeth", International Journal of Power Electronics and Drive Systems (IJPEDS), Vol. 6, No. 4, December 2015, pp. 853-859.
2. **S.M.Al-Habshi**, M.L. Mohd Jamil, M.N. Othman, A. Jidin,K. Ab Karim,Z.Z. Zolkapli, 'Influence of Number of Turns Per Coil in Fractional-Slot PM Brushless Machines' : IEEE Conference on Energy Conversion-CENCON 2014, October 13-14 2014, Johor Bahru Malaysia, pp. 146-151.
3. M.L. Mohd Jamil, Z.Z. Zolkapli, A. Jidin, **S.M.Al-Habshi**, M.N. Othman, 'Electromagnetic Performance of High-Torque and Low-Speed PM Brushless Machine': IEEE 8th International Power Engineering and Optimization Conference (PEOCO 2014), March 24-25 2014,Langkawi Malaysia, pp. 653-657.

CHAPTER 1

INTRODUCTION

1.0 Background

The discovery of rare-earth magnets such as Ferrite, Alnico, Samarium-Cobalt and Neodymium-Iron-Boron in last thirty years has led to an invention of Permanent Magnet machine topology. This machine topology gives some advantages that made it reliable for many applications, ranging from small consumer products and up to heavy industry systems. Simpler design and construction, a relative low cost for some basic design, high winding factor, zero electrical losses due to an absent of field excitation, high air gap flux-density, high torque density, improved dynamic performance i.e. possible optimum flux weakening are the advantages that have been obtained (Gieras and Wing, 2002). In addition, an absent of field excitation results a relative low maintenance as mechanical commutation is disappeared. The electronic commutation takes charge externally via an electronic motor drives.

The BH curve of permanent magnets are illustrated in Figure 1.1 (Krishnan, 2010). Neodymium and Samarium Cobalt are classified as rare-earth magnets while the other two i.e. Ferrite an Alnico are ceramics and metal respectively. Magnet which properties consist of high remanent flux-density and high coercivity may not easily to be demagnetized by taking into account the worst case of temperature condition. A coercive force indicates how strong the magnet can sustain an amount of current through that produces magnetic intensity inside electrical machine while magnetic remanent indicates the flux density level in free space like an air. As compared to other types of permanent magnet, Neodymium and Samarium Cobalt are generally preferable for optimum motor design due to high magnet remanent, high coercivity, and linear characteristics. For high temperature condition, Samarium-Cobalt is preferable than Neodymium as the Neodymium has limited temperature range but the Samarium-Cobalt itself is relatively hard in machining. Neodymium magnet is considered the best choice as it can be fabricated into sintered and bonded forms respectively. The sintered form can give best characteristics but high in cost while the bonded form gives lower characteristic, relatively easier in machining and low cost in fabrication.

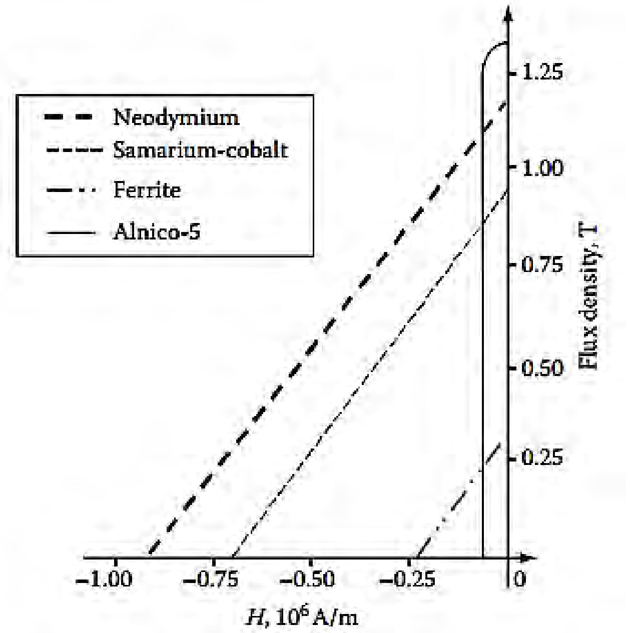

Figure 1.1: Second quadrant of PM BH curve

Conventionally, Permanent Magnet machines are designed similarly to other electric machines which flux distribution moves radially in a cylindrical shape motor design. For radial type of machine, a rotor can be placed either internally or externally which later called as internal rotor and external rotor. These two machines may have similar electromagnetic characteristics if same machine parameters are considered accomplishing the same desired output torque performance (Kazmin et al., 2008).

The slot-number, N_s, winding types and magnet pole numbers, $2p$ must be properly determined for an optimum electromagnetic characteristic. Various combinations of slot-number and pole-number will inherently result possible winding configurations. Two common types of winding configurations influenced by the various combinations of slot-number and pole-number are called Integral-Slot and Fractional-Slot respectively. An integral-slot machine is defined when a number of slot per pole per phase, q, equals to 1,2,3,.., while a fractional–slot machine takes place when q is a fraction such as 0.375, and 0.5.

The distributed, concentrated and alternate-tooth winding configurations are among winding techniques that are commonly used in researches of electric machines nowadays. Each method has it own contribution in machine design. The distributed winding produces a low torque ripple but requires longer end winding. While concentrated winding requires shorter end windings and easy to construct, but a high cogging torque may exists due to the influence of smaller slot-number and pole-number respectively. An alternate-teeth wound machine has higher winding factor, Kw, than the one with concentrated wound, inherently results higher back-emf, higher output torque and lower torque ripple (Zhu et al., 2006). Moreover, an alternate-tooth wound machine with unequal tooth width is more superior due to a relative high of phase flux -linkage with “more trapezoid” waveform (Ishak et al., 2005).

Instead of copper and core losses that commonly exist in many electrical machines, PM machines may exhibit a radial magnetic pull or radial unbalanced force which can cause vibration. This radial magnetic pull exists due to asymmetric winding disposition of machine that has similar slot and pole numbers. This phenomenon is also known as an Unbalanced Magnetic Force (UMF), as the radial force existed in each phase's coils are not cancelled each other (Zhu et al., 2011, Zhu et al., 2009). Severe stator deformation and high acoustic noise may occur when the vibration frequency matches with the core natural frequency.

1.1 Research Motivation

The significant advantages of PM machines in both construction and electromagnetic characteristics have attracted electric machine designer to consider the PM machines as an alternative instead of other conventional electric machines. However, some configurations of PM machines may exhibit an UMF naturally. This is due to the asymmetric disposition of phase windings. The UMF has to be eliminated as it may result vibration in the PM machine. Several researchers have introduced some methods to reduce UMF and vibrations, however, none of them were discussed on reducing it in on load condition. Investigations on the UMF phenomenon in fractional-slot PM motors that are equipped with asymmetric disposition of phase windings are carried out for the elimination purpose.

1.2 Problem Statement

The UMF in some PM machines equipped with fractional-slot windings is inherently existed. The design trade-off for this type of machines such a good back-emf profile, high torque density and a relatively low cogging torque. However the UMF will never disappear except a slight reduction when different number of rotor pole is equipped.

An effort to eliminate UMF by maintaining other electromagnetic characteristic above is a challenge. It is believed that the noise and vibration have strong relation with the UMF as the reduction of UMF may influence the change of noise and vibration levels significantly.

1.3 Research Objectives

As the main subject of investigation is a reduction technique of UMF in PM machines. Several modifications to stator design parameters of PM machines are carried out by ensuring similar electromagnetic performance as the electromagnetic performance of earlier design of machines is desirable. The research objectives in this investigation are as follows:

1. To investigate the influence of un-even number of coil turns per phase and asymmetric stator on UMF.
2. To investigate a correlation between a UMF and vibration in PM machines.
3. To verify the proposed technique by validity the predicted and measured results of the design prototypes.

1.4 Scope of Research

This research is focused on the Fractional-slot PM machines equipped with surface mounted permanent magnet. Since the combination between slot-number and pole number differs by one, the machine stator is inherently equipped with the asymmetric disposition of phase winding. The radial field machine that operates in BLDC mode and energized by trapezoidal current. Initial design calculations were carried out by Motorsolve software and behavioral analyses were conducted via ANSYS Finite-Element Analysis software. The electromagnetic characteristics such as open circuit flux density, back-emf, output torque, UMF and cogging torque are included in the investigation as there will also be affected by the design modifications. The UMF is still the main focus as there is a need to eliminate for the purpose of reduction of noise and vibration. Due to limited facilities on UMF measurement, the design modifications are partially verified by the behavior of back-emf and output torque.

1.5 Research Contribution

This research provides an expansion of new knowledge of UMF in PM machines. A simple technique to reduce UMF in Fractional-slot PM machines that equipped with asymmetric phase windings is presented. It shows that the radial and tangential force density components of UMF are influenced by the configuration of un-even number of turns per coil in every phase winding. The radial force density shows a slight reduction while the tangential force density almost remains unchanged, but there is a slight reduction of torque performance. A correlation between an UMF and vibration is also discussed together where the influence of un-even number of coils per phase and stator asymmetry affect the UMF trend/behavior initially.

1.6 Thesis Outline

The overall structure of the research is distributed into five chapters, including an introductory chapter as Chapter one. This Chapter One consists of research background, research motivation, problem statement, research objectives, research scope, research contribution and thesis outline.

Chapter Two consists of basic information about PM machine topology, review on performance analysis and recent development of Fractional-Slot PM Machine equipped with concentrated windings. Related works on UMF and basic correlation with vibration information on PM machines are highlighted. A proposed work on UMF analysis that able to fill the research gap is also presented in the last part in this chapter.

Chapter Three presents basic design procedures; basic calculation of machine design for a given specific rated performance and two potential approaches in minimization of UMF is presented. Initial analyses on the electromagnetic performance and the behavior of UMF in specified PM machines are also presented. The experimental setup for back-emf, output torque and are also included in the last part.

Chapter Four presents a detailed comparison between initial design of specified machines and modified ones for the purpose of verification. This includes a comparison between the predicted results from finite-element analysis and measured results from measurement. An analysis between UMF and vibration is also presented as a part of verification.

Chapter 5 concludes various aspects of the research works that have been presented and includes potential suggestions for future work.

Appendices A-D provides additional information such as extra results from 15-slot machine, AutoCAD designs, magnet datasheet and experimental setup.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter discusses general information of Permanent Magnet Machines. It covers basic construction and topologies, operating principle and its applications. The literature has also been focused on the related issues of UMF.

2.1 Motor Topologies

Conventionally, two machine topologies i.e. radial and axial field machines are used in permanent magnet machine.

2.1.1 Radial-Field Machine

The radial field topology can be designed with either interior or exterior rotor. The magnetic field moves along the magnetic path, i.e. from rotor to stator in radial direction as shown Figure 2.1. Both machines may have similar electromagnetic characteristics and rated performance i.e. output torque if similar machine parameters are considered (Kazmin et al., 2008). Some rotor topologies of radial machine are briefly explained in the following section. Figure 2.2 (Amemiya et al., 2005, Dajaku and Gerling, 2007) illustrated general rotor topologies for the radial field machine.