Faculty of Electrical Engineering

INFLUENCE OF TOOTH DESIGNS ON ELECTROMAGNETIC CHARACTERISTICS IN FRACTIONAL-SLOT PERMANENT MAGNET BRUSHLESS MACHINE

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DECLARATION

I declare that this thesis entitled “Influence of Tooth Designs on Electromagnetic Characteristics in Fractional-Slot Permanent Magnet Brushless 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

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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 who always believe in my dreams

ABSTRACT

Due to factors such as a simpler construction and high torque density, the Permanent Magnet (PM) electric machines are favorable as an alternative to other conventional machine topologies. However, the PM machines may result high torque ripple due to the influences of cogging torque and electronic commutation respectively. In this research, an influence of various stator tooth designs on the electromagnetic characteristics in Fractional-Slot PM machines is investigated using 2D Finite-Element Analysis software, Ansys Maxwell. The influences of having additional thin PM on stator tooth-tip, asymmetric design of stator tooth-tip and the notch numbers and notch dimension are investigated for the purpose of torque ripple reduction at rated condition without degrading the average torque. By introducing these factors, the existing flux flows along the stator iron path would be affected leading to a potential change on the machine's electromagnetic characteristics. The research has focused into the twelve-slot/ten-pole motor equipped with alternate tooth winding as it results more trapezoidal back-emf and lesser torque ripple. From the investigation, it is confirmed that a reduction of high torque ripple leading to a more constant torque at rated condition is desirable. It is also found that the machine which stator is modified has a significant reduction of torque ripple at about thirty-nine percent. For a verification purpose, the prototype motor design which is based on the lowest output torque ripple is developed and tested. A good agreement between predicted and measured results is achieved. The prototype design is then proposed for the application of robotic system.

ABSTRAK

Faktor-faktor seperti pembinaan yang ringkas dan ketumpatan daya putaran yang tinggi menjadikan mesin-mesin elektrik berasaskan Magnet Kekal (PM) kian disukai sebagai pengganti kepada mesin-mesin elektrik konvensional yang lain. Walau bagaimanapun, mesin-mesin elektrik berasaskan Magnet Kekal mungkin akan menghasilkan riak daya putaran yang tinggi disebabkan oleh pengaruh daya putaran gigian dan penggantian elektronik. Dalam kajian ini, pengaruh daripada pelbagai rekabentuk gigi pemegun terhadap sifat-sifat elektromagnet dalam mesin Pecahan-Slot Magnet Kekal disiasat menggunakan analisa Unsur-Terhad 2D. Pengaruh kesan tambahan Magnet Kekal nipis pada hujung gigi pemegun, rekabentuk tidak simetri pada gigi pemegun, dan jumlah takuk dan ukurannya disiasat bagi tujuan pengurangan riak daya putaran pada keadaan berkadar tanpa mengurangkan purata daya putaran dalam keadaan berkadar. Dengan memperkenalkan faktor-faktor ini, pengaliran fluks yang sedia ada di laluan besi pemegun akan diganggu membawa kepada potensi perubahan terhadap sifat-sifat elektromagnetik dalam mesin. Kajian ini telah memfokuskan kepada konfigurasi motor dua belas-slot/sepuluh-kutub yang dilengkapkan dengan gegelung pada gigi pemegun secara berselang-seli yang mana ia secara asasnya menghasilkan voltan balikan yang lebih trapezoid dan kurang riak pada daya putaran. Daripada penyiasatan, adalah pasti bahawa pengurangan riak daya putaran membawa kepada keadaan daya putaran yang lebih malar boleh dicapai pada keadan berkadar. Didapati juga mesin yang mempunyai bentuk pemegun yang diubah memperolehi pengurangan riak daya putaran yang signifikan sebanyak tiga-puluh sembilan peratus. Bagi tujuan pengesahan, rekaan prototaip berasaskan riak daya putaran yang paling rendah dibangunkan dan diuji. Rekaan prototaip tersebut kemudain dicadangkan bagi penggunaan dalam aplikasi sistem robotik.

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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. Mohd Jamil, **Z. Z. Zolkapli**, A. Jidin 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. 860-868.
2. **Z. Z. Zolkapli**, M. L. M. Jamil, S. M. Al-Habshi, A. Jidin And M. N. Othman, ‘Torque Ripple Minimization Technique In Fractional-Slot PM Brushless Machines’: 2014 IEEE Conference on Energy Conversion (CENCON 2014), October 13-14 2014, Johor Bahru Malaysia.
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.
4. 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.

CHAPTER 1

INTRODUCTION

1.0 Background

In modern world, robotic field benefits mankind as it able to assist human in handling non-complex and complex daily tasks either ranging from small consumer applications and up to heavy industrial works. A high demand of robotic applications system in military and bio-medical engineering industries exists due to limited human physical capability that may result desired outcomes.

Although numerous robots have been designed to replace some specific human jobs to simplify daily tasks like to serve both healthy and disabled people, a brilliant solution nowadays is to combine human decision wise and robotic action for a better result. As the human becomes part of the system, it intelligence decision has improved the dynamic response in performing specified task.

An exoskeleton robotic system is an alternative system that represents the combination of human and robot action. For example, a bionic arm may consist of an external structural mechanism that is linked to some parts of human body to boost the capability of the human arm. It is simply a wearable hybrid robot that is attached to the subjected limb that can generate desired movement. The human brain is a main controller for this mechanism. With an assistance of firm mechanical system, extra works i.e. due to extra burden or load is achievable.

The design of an exoskeleton robot system needs special considerations as the system interacts directly with the human (Gopura et al. 2015). Special design of actuators used for the system is very important because each actuator could affect the driving reliability and efficiency of the robotic system. This fact necessitates the use of machines that have high power-to-weight ratio leading to a main selection criteria for the design exoskeleton actuators.

An electrical motor, a pneumatic muscle, hydraulic and hybrid systems are the candidates for the actuating part of an exoskeleton robot. Previous research has shown that the electric motors is more favourable than the pneumatic muscle and other system such hydraulic and other means, and they are divided into 65%, 25% and 10% respectively (Gopura et al. 2015). The limitation of pneumatic and hydraulic actuators is due to the required bulky solenoid air valves and oil pumps which make the exoskeleton robot system less portable.

Within the electric motor category, permanent magnet (PM) brushless motor type offers several advantages such as high efficiency, low copper loss, high winding factor, high torque density and simpler structure. These advantages becoming crucial in order to attain high torque-low speed performance together with a slim design shape for robot joint module. However, high torque ripple, high cogging torque, large unbalanced magnetic pull and high rotor loss are some of the drawbacks in the PM motor types. Thus, a care should be taken during design stage so that the drawbacks could be minimized as much as possible especially when there is a need to have a high performance motor for high performance applications.

An elimination of torque ripple can be endeavoured in two ways; i) motor design approach; and ii) an intelligence control of electrical drives. A proper design of electric motor is a must as it can reduce output torque density and efficiency and inherently increases manufacturing cost. Therefore, design optimizations are substantial concern in developing well-designed machine where a parasitic effect like high torque ripple and large unbalanced magnetic pull can be avoided.

From motor design perspective, the PM motors are theoretically can be designed and analysed via analytical calculation or Finite-Element Analysis (FEA). When PM motors are loaded, the torque ripple of the developed torque is commonly due electronic commutation while the presence of permanent magnet has great influence on the torque ripple when the motors are not excited. However, a strange behaviour of torque ripple may exist due to the design imperfections on the stator and rotor dimensions. Severe undesirable noise and vibration may exist in a low speed performance of small PM motors. A strong permanent magnet effect also dominates the magnetic path of the respective motor.

Instead of electronic commutation, the torque ripple is also resulted by the size of cogging torque in PM motors. Thus, the minimization of cogging torque becomes an important thing in the design stage of PM motor. Previous researches have shown that there are various effective techniques can be implemented for cogging torque minimization i.e. stator or rotor skewing (Islam et al. 2009), magnet pole shape (Upadhayay & Rajagopal 2013), pole arc coefficient (Shah et al. 2012), magnet shifting (Dosiek & Pillay 2007), and stator teeth notching (Xia et al. 2013). It is also possible to implement more than one techniques in order to eliminate the cogging torque, but care should be taken as it may affect back-emf and electromagnetic torque performance. The teeth notching helps to reduce skewing angle of rotor magnet which sometimes results manufacturing problem and retain the shape of back-emf (Zhang et al. 2008), (Bianchi & Bolognani 2002), (Islam et al. 2004).

As the cogging torque is one of the components of torque ripple, many researches have confirmed that the reduction of cogging torque reduces the torque ripple. However, in some cases the torque ripple is still high even the cogging torque is significantly reduced (Wang et al. 2013). Then the torque ripple is effectively reduced by not only due to cogging torque but due to other sources as well (Islam et al. 2004). Hence, investigations on the torque ripple are very important by means of minimization techniques in motor design.

1.1 Problem Statement

An electric motor embedded as an actuator, for example used in an exoskeleton robot must have a compromise between small physical size and high torque density. Otherwise, the motor will limit the overall efficiency of the system even though having good electromagnetic performance. A specific design size due to mechanical factors inherently causes the designing process is rather a complicated task. This is due to the correlation between rotor volume and the production of an electromagnetic torque. For this reason, an optimal motor design with respect to a specific overall motor size and output torque capability requires a good compromise.

Furthermore, the developed torque usually produces high torque ripple due to design imperfections and the presence of permanent magnet itself that tends to align to the stator slot despite when there is no winding excitation. Motor with high torque ripple may causes of undesirable noise and vibration especially in small motor with strong permanent magnet at low speed operation. Thus, minimizations of torque ripple becoming an important characteristic for high torque-low speed machines.

1.2 Research Objectives

The aims of the research are to design and develop a high torque low speed motor for robotic application. The motor should be capable to meet performance specification such as high electromagnetic torque and low torque ripple at specified low speed condition. The objectives are formulated as follows;

1. To design and analyse a high-torque low-speed BLDC motor which output torque has an average of 10Nm.
2. To study the influence of tooth designs on the electromagnetic performance such as back-emf, electromagnetic torque and cogging torque.
3. To fabricate and test the proposed design prototype for verification purpose.

1.3 Scope of Research

This research focuses on the development of high-torque, low-speed PM brushless motor which is used as an actuator for exoskeleton robot-bionic arm. The main specification of the motor design is 10 Nm and low rated speed of 100 rpm. The prototype motor design should have a slim size but having a relative high electromagnetic torque density where the design is based on the current-density concept. The initial design parameters are calculated by using *Motorsolve* software to create a truly customized modeling of motor structure where saturation condition is negligible. For optimization purpose, the design is then analysed by using 2D Finite-Element Analysis, Ansys Maxwell in which saturation effect is taken into account. The influences of the proposed design on the motor electromagnetic performance are analysed and verified via testing and measurement.

1.4 Significance of Research

This research is endeavoured for the purpose of development of high performance motor for low-speed application of exoskeleton-robot. The exoskeleton robot system is targeted to have an embedded direct-drive of electric motor which later may simplifies the overall system structure. On the other hand, improving torque performance by eliminating output torque ripple is a must as it may help accurate position control of the respective PM motor. From design perspective, a modification on stator magnetic path by modifying the stator or rotor iron core able to influence the electromagnetic performance such as back-emf, cogging torque and output torque respectively. The proposed technique has significantly reduced the torque ripple amplitude while maintaining the average output torque.

1.5 Thesis Outline

The overall structure of the research is distributed into five chapters. A general overview of the research is presented in Chapter One where the research background, problem statement, research objectives, scope of research, significance of research and thesis outline are included.

Chapter Two presents a brief history of PM brushless motor including the theoretical design aspects such as stator and rotor topologies, geometry shape and winding configurations. A review on torque ripple reduction techniques for PM brushless motor is