UNIVERSITI PUTRA MALAYSIA

DESIGN OF A HIGH FUNDAMENTAL TORQUE SINGLE PHASE DOUBLE STATOR BRUSHLESS DC MOTOR

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By

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

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Single phase brushless DC motors (BLDC) are adopted for many low cost applications such as in fans, blowers and other domestic appliances. Recently, single phase BLDC motors are used for portable application such as the mechanical chopper, cutter and grinder. The requirement for such type of motor application is high torque density. However, consideration in the qualities of torque waveform is required in determine the torque density. This is because the fundamental torque which shows the average torque should be used as the torque values compare to maximum torque in calculating the torque density. Maximum torque with large distortion of torque waveform which means that high *THD* value is not acceptable since does not contributes higher average torque. Besides, low *THD* in torque waveform subject less ripple and vibration on the motor performance. All of this can be derived by properly design magnetic circuit of BLDC motor. Hence, the motivation of this research work is to design a BLDC motor that has high fundamental torque and low THD by improvise its magnetic circuit.

Finite Element Analysis (FEA) is used to analyze the magnetic characteristic including the electro-magnetic torque characteristics in this research. For all cases, volume of the permanent magnet is fixed at 400 mm^3 per each pole. The coil magnetomotive force is set for 480 AT per pole. Initially, parallel magnetic circuit in typical type BLDC motor is being studied including the flux distribution, air-gap flux density, and torque characteristic with their harmonic components. Then, several magnetic circuit designs in single and double stator are proposed to overcome the limitation of typical type BLDC motor. Further, analysis on the taper parameters that affect the torque characteristics is carried out among proposed magnetic circuit in BLDC motor.

Determination for maximum torque (max. T_m), minimum cogging torque (min. $T_{c)}$, maximum fundamental torque (max. T_f), and minimum total harmonic distortion (min. *THD*) are used to select the best model for fabrication. Several proposed magnetic circuits of BLDC motor is fabricated and experimentally evaluated. The simulation results from the FEA analysis are verified with the measurement result. For comparative analysis, motor constant square density, *G* is used. It can be seen that the motor constant square density, *G* for single stator *Typical SS Parallel* and *SS Series* are 5.54 and 8.54, respectively. Meanwhile, motor constant square density, *G* for double stator *DS Parallel*, *DS Series A* and *DS Series B* are 2.365, 4.24, and 15.0, respectively. Therefore, it shows that double stator type *DS Series B* is the best choice among all motors that been studied. In conclusions, the research proposed an optimal magnetic circuit configuration that could provide high fundamental torque and low *THD*. Finally, this thesis provides guidelines**,** suggestions and proposes better magnetic circuit in designing BLDC motor.

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

MEREKABENTUK DAYA PUTARAN ASAS YANG TINGGI MOTOR DUA PEMEGUN BERARUS TERUS TANPA BERUS SATU FASA

Oleh

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Motor Satu Fasa Tanpa Berus (BLDC) diguna pakai untuk banyak aplikasi kos rendah seperti dalam dalam kipas, peniup dan lain-lain peralatan domestik. Baru-baru ini, motor satu fasa BLDC yang digunakan untuk aplikasi mudah alih seperti pemotong mekanikal, pemotong dan pengisar. Keperluan untuk aplikasi motor jenis ini ialah tork kepadatan tinggi. Walau bagaimanapun, pertimbangan dalam qualiti gelombang daya putaran diperlukan dalam menentukan kepadatan daya putaran. Ini adalah kerana daya putaran asas yang menunjukkan purata daya putaran boleh digunakan sebagai nilai daya putaran berbanding dengan daya putaran maksimum dalam pengiraan kepadatan daya putaran. Daya putaran maksimum dengan ganguan besar gelombang daya putaran yang bermaksud bahawa nilai THD tinggi tidak boleh diterima memandangkan tidak menyumbang daya putaran purata yang lebih tinggi. Selain itu, THD rendah dalam bentuk gelombang daya putaran tertakluk kepada kurang riak dan getaran pada prestasi motor. Semua ini boleh diperolehi dengan mereka bentuk litar magnet BLDC yang betul. Oleh itu, motivasi kerja penyelidikan

ini adalah untuk mereka bentuk motor BLDC yang mempunyai daya putaran asas yang tinggi dan THD yang rendah dengan penambahbaikan litar magnet tersebut.

Analisis Unsur Terhingga (FEA) digunakan untuk menganalisis ciri-ciri magnetik termasuk ciri-ciri daya putaran elektro-magnet dalam kajian ini. Bagi semua kes, jumlah magnet kekal ditetapkan pada 400 mm^3 bagi setiap tiang. Gegelung kuasa magnetomotif ditetapkan untuk 480 AT setiap tiang. Pada mulanya, litar magnetik selari dalam motor BLDC jenis biasa dikaji termasuk pengagihan fluks, ketumpatan fluks jurang udara, dan ciri-ciri daya putaran dengan komponen harmonik mereka. Kemudian, beberapa rekabentuk litar magnetik dengan satu dan dua pemegun dicadangkan untuk mengatasi kekangan motor BLDC jenis biasa. Seterusnya, analisis pada parameter tirus yang memberi kesan kepada ciri-ciri daya putaran dijalankan untuk litar magnetik yang dicadangkan dalam motor BLDC.

Penentuan bagi daya putaran yang maksimum (maksimum T_m), daya putaran cogging yang minimum (minimum T_c), daya putaran asas yang maksimum (maksimum T_f) dan jumlah herotan harmonik yang minimum (minimum *THD*) digunakan untuk memilih model terbaik untuk fabrikasi. Beberapa cadangan litar magnetik motor BLDC difabrikasi dan eksperimennya dinilai. Keputusan simulasi daripada analisis FEA telah disahkan dengan keputusan pengukuran. Untuk analisis perbandingan, pemalar kepadatan motor kuasa dua, *G* digunakan. Ia boleh dilihat bahawa pemalar kepadatan motor kuasa dua, *G* untuk motor BLDC satu pemegun "*Typical SS Parallel*" dan "*SS Siri*" adalah 5.54 dan 8.54 masing-masing. Sementara itu, pemalar kepadatan motor kuasa dua, *G* untuk motor BLDC dua pemegun "*DS Parallel*, *DS Series A dan DS Series B*" ialah 2.365, 4.24, dan 15.0 masing-masing. Oleh itu, ia menunjukkan bahawa motor BLDC dua pemegun jenis *DS Series B* merupakan pilihan yang terbaik di kalangan semua motor yang dikaji. Dalam kesimpulan, kajian ini mencadangkan konfigurasi litar magnetik yang optimum yang boleh memberi daya putaran asas yang tinggi dan THD yang rendah. Akhirnya, tesis ini menyediakan garis panduan, cadangan dan mencadangkan litar magnetik yang lebih baik dalam merekabentuk motor BLDC.

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I certify that a Thesis Examination Committee has met on 16th May 2013 to conduct the final examination of Raja Nor Firdaus Kashfi Raja Othman on his Doctor of Philosophy thesis entitled "**Design of A High Fundamental Torque Single Phase Double Stator Brushless DC Motor**" in accordance with Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the candidate be awarded the Doctor of Philosophy. Members of the Thesis Examination Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Putra Malaysia or other institutions.

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RAJA NOR FIRDAUS KASHFI

Date: 16 May 2013

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

B	Magnetic flux density in (T)
ϕ	Flux (Wb)
A	Area of perpendicular to flux direction in (m^2)
$\Im$	Air gap area (m^2)
N	Number of coil turn (T)
I	Input current
H	Magnetic field intensity
l	Length of coil turn
u	Absolute permeability of material
$\Re$	Reluctance in (Ω)
P	Permeance in (H)
B_c	Flux density of coil (T)
B_{ag}	Flux density of airgap (T)
A_{ag}	Area of airgap flux density of coil (T)
L	Inductance (H)
ψ	Flux linkage
B_{ag_outer}	Outer air-gap flux density (T)
B_{ag_inner}	Inner air-gap flux density (T)
$W_s°$	Slot width
$W_r°$	Rotor width
H_{spt}	Height of stator pole teeth
H_{rth}	Height of rotor teeth
H_{sps}	Height of stator pole shoe
$W_{os}°$	Outer stator width
$W_{or}°$	Outer rotor width
W_{is}	Inner stator width
$W_{ir}°$	Inner rotor width.
T_m	Maximum torque or peak torque
T_c	Cogging torque

T_f,	Fundamental torque
THD	Total harmonic distortion

I certify that a Thesis Examination Committee has met on (16 May 2013) to conduct the final examination of (Raja Nor Firdaus Kashfi Raja Othman) on his (or her) thesis entitled "**Design of A High Fundamental Torque Single Phase Double Stator Brushless DC Motor**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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CHAPTER 1

INTRODUCTION

1.1 Background

The advancement in the permanent magnet technology has brought major impact in the electrical machine field. With advantages of such high efficiency and compact size, permanent magnet is used to form the fundamental field replacing the field winding in machines. Extensive usage of high energy permanent magnet has brought better thrust densities and energy conversion ratios has made it as a competitive machine for almost all the applications in recent times. The growths in the power electronic technology enhance the control of operation of such machines [1, 2].

In conjunction with the growths in the power electronic technology, development of the permanent magnet motor developed in this investigations pave way to improvise the torque density through the magnetic circuit analysis. The main advantage of permanent magnet structure is that it can be operated as a brushless or as a synchronous motor. Moreover, this motor has a structure that enables for broader applications, especially applications that require high torque and speed. Interior permanent magnet topology is widely used since it has mechanical strength in the rotor assembly compared to the surface permanent magnet topology since this motor is used for high torque application [3].

For brushless, a strong electromagnetic force exists between the rotor permanent magnets and the stator coils. The brushless DC permanent magnet is usually driven by sinusoidal currents or rectangular currents, depending on the motor back electromotive force (EMF) waveforms [4-6]. The brushless DC permanent magnet has the features of high-power density, high overload and wide range of weak magnetic, which is much suitable for variable load application. With such advantages, the brushless DC permanent magnet has been widely used in electric vehicles. The brushless DC permanent magnet operates as bidirectional variable speed operation under full torque mode. However, the operation of the brushless DC permanent magnet motor essentially requires a rotor position sensor for proper commutation.

This thesis presents design of high fundamental torque and low THD of single phase brushless DC permanent magnet motor. Finite Element Analysis (FEA) is used to simulate the magnetic characteristic including the torque waveform in this research. Firstly, parallel magnetic circuit in typical BLDC motor is being studied including the flux distribution, airgap flux density, torque characteristic and harmonic components. Based on the study result, several magnetic circuits design is proposed. Analysis on the taper parameters that affect the torque characteristics is being carried for propose magnetic circuit brushless DC permanent magnet motor. The analysis is to identify the factors that contribute to the sinusoidal torque waveform. Determination of minimum total harmonic distortion (min. *THD*), the maximum fundamental torque (max. T_f), the maximum torque (max. T_m) and the minimum cogging torque (min. $T_{c)}$ are used for the selection of the best model for fabrication. The proposed magnetic circuit of single phase brushless DC permanent magnet motor are fabricated and measured. The simulation result of FEA is verified with the measurement result. For comparison, motor constant square density, *G* is used for evaluation to all models.

1.2 Problem Statement

Single phase brushless DC permanent magnet motors (BLDC) are adopted in many low cost applications such as in fans, blowers and other domestic appliances [7-11]. The main disadvantage of using single phase compared to three phase permanent magnet motor is the inability to self-start [11-13]. However, for specific application such as the mechanical chopper, the single phase motor is the most popular application due to the safety consideration. Such limitation of size, space, weight and volume that usually required for portable application such as mechanical chopper as mention above gives bigger drawback in designing a high torque density single phase BLDC motor. However, consideration in the qualities of torque waveform is required in determine the torque density. This is because the fundamental torque which shows the average torque should be used as the torque values compare to maximum torque in calculating the torque density. Maximum torque with large distortion of torque waveform which means that high *THD* value is not acceptable since does not contributes higher average torque. Besides, low *THD* in torque waveform subject less ripple and vibration on the motor performance.

However, a few numbers of researchers doing research on the single phase motor structure or its magnetic circuit to improve the torque value thus improves the torque density. Many of researchers are focus on commutation and driver control of single phase brushless DC motor which does not involve the motor design [14-18]. Most of the researchers study to eliminate the dead point so that the single phase brushless DC motor can move without applying external force to the rotor during starting period. Some of them studied on the improvement of torque characteristics quality such as torque ripple and cogging torque [19-20].

Conventional method to increase the torque value is by increasing the magnetic energy which can be realized by resizing the permanent magnet volume or applying larger number of coil turn [21-24]. However, the flux density in some parts of stator or rotor of permanent magnet motor leads to saturation value if volume of permanent magnet is increase [25-27]. In addition, a high torque motor usually comes with high cogging characteristic that introduce the torque ripple in the torque characteristic. Whereas, a pure sinusoidal torque characteristic ensures uniform flux distribution that produce smooth speed rotation [28-30]. Nevertheless, such pure sinusoidal torque characteristic is hard to achieve in the presence of permanent magnet that caused the cogging torque. Therefore, conventional method that increases the magnetic energy cannot be used for designing high torque motor.

Therefore, this research would like to focus on the motor structure based on the design of new magnetic circuit configurations so that the torque value can be increased. A good magnetic circuit produced optimum air gap flux density that perpendicular to the air gap surface so that high torque density motor with high fundamental torque and low THD can be achieved. Currently, a high torque density brushless DC permanent magnet motor is required in order to meet the recent demands in portable application.

1.3 Objectives

Based on the discussed problem statement above, several objectives have been identified for this research. These objectives are listed as below:

1. To compute typical parallel magnetic circuit in single phase BLDC motor for clear understanding of its limitation and performance.
2. To design and propose magnetic circuit that produce high fundamental torque and low THD in single phase BLDC motor.
3. To analyze the effect of taper parameters on maximum torque, cogging torque, fundamental torque and total harmonic distortion of propose magnetic circuit in single phase BLDC motor.
4. To determine the minimum Total Harmonic Distortion (min. *THD*), the maximum fundamental torque (max. T_f), the maximum peak torque (max. T_m) and the minimum cogging torque (min. T_c) of propose magnetic circuit single phase BLDC motor.
5. To compare the measurement result with simulation result of the static torque characteristics for verification purposes.

1.4 Thesis Contributions

The main contribution of the thesis is the proposal several design of magnetic circuit design that produce higher fundamental torque and low THD of torque waveform is compare with typical single phase BLDC. Finally, magnetic circuit that produce highest fundamental torque and low THD of torque waveform among all proposed magnetic circuits is selected for fabrication and justify using motor constant square density, *G*. For knowledge contribution aspect, the theoretical explanation of such improvement of torque value for each proposed magnetic circuit is investigated using Finite Element Analysis (FEA). Besides, the analysis on the taper parameter discloses the design parameter of taper that could be used in achieving a lower total harmonic distortion, *THD* of torque waveform. This provides guidance for other researcher in selecting the best possible of taper in designing any brushless DC permanent magnet motor.

1.5 Scope of Work

In this research, the improvement of magnetic circuit in brushless DC permanent magnet motor carried out via Finite Element Analysis (FEA). The FEM software package known as FEMAPH developed by Masami Nirei, Professor of Nagano National College and Technology, Japan can determine the availability of magnetic characteristics such as flux flow, magnetic density, and torque distribution. The research focuses only for single phase BLDC motor topology due to safety consideration for specific application such as mechanical cutter and chopper.

Another scope of this research is the design of single phase BLDC motor that have high fundamental torque and low THD of torque waveform by investigating possible magnetic circuit. This research does not conduct details study on the contribution of losses of the proposed magnetic circuit design in details. This means that the research don't determine value of losses such as Eddy current loss, iron loss, copper loss and hysteresis loss. Nevertheless, dynamic measurement such as torque and speed; input power and speed; output power and speed; and efficiency is carried out for the fabricated motor in this research.

1.6 Thesis Outline

Chapter One gives an overview about this research. It includes an introduction about the research, problem statement, scope of work and objectives of the research. The introduction explains in general about brushless DC permanent magnet motor and its recent application. Moreover, the problem statement addressed the motivations to carry out this research. The listed objectives show the determination of aim that is required for this research. Besides, the scope of work gives an outline about the methodology focused in this research.

Chapter Two discusses the magnetic circuit in general which reflect the main contribution of the research. This chapter also discusses about the brushless of DC Motor includes the basic structure, operation and comparison to brush DC motor. In addition, comparison of DC, synchronous and stepper motor is presented to enhance reader understanding about the selection of brushless DC motor for this research. This chapter also discusses about several related research of single phase brushless DC motor that had been presented in various literature. Lastly, this chapter also discusses about the definition of torque characteristic component that used in the analysis of this research.

Chapter Three describes methodology of the overall research. An explanation about the simulation methodology using Finite Element Analysis (FEA) is presented. Then, initial motor parameter in the overall research is discussed. Next, parallel magnetic circuit of typical brushless DC permanent magnet motor is presented. This study helps the viewer to understand the limitation and performance of parallel magnetic circuit of typical brushless DC permanent magnet motor. Based on the study result, the several magnetic circuits design is proposed. Furthermore, the theoretical explanation of such several magnetic circuits design that could produce higher torque is presented using Finite Element Analysis (FEA). Next is the methodology of the analysis of the effect of taper parameters in several magnetic circuits design of the proposed single phase BLDC is presented. Furthermore, the calculation method for torque and speed characteristic of dynamic calculation is also shown. In addition, the measurement setups for static and dynamic torque characteristic are also shown.

Chapter Four discusses the analysis result taper parameter effect of parallel magnetic circuit and proposed series magnetic circuit in single phase BLDC motor. Furthermore, evaluation result on all magnetic circuits design in brushless DC permanent magnet motor is also presented in this chapter. In this evaluation four types model is selected from each magnetic circuits design for fabrication selection. Several models of proposed magnetic circuits design in this research are selected for fabrication and the result of simulation is verified by the measurement. For final comparison, motor constant square density is used to compare the typical and proposed design of magnetic circuits in this research.

Chapter Five presents the conclusion of overall research in term of the design process and the analysis result. This chapter also includes a few recommendations that can be implemented in this research field in future.

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