DESIGN AND DEVELOPMENT OF A SMALL-SCALE 12S-14P OUTER ROTOR HEFSM

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To my beloved family.
Thank you for your prayer and support.
I love you all.

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ABSTRACT

Simulation, prototype experimental, and mathematical modelling is an essential process to provide sufficient evidence before a full-scale development or mass production. Hence, this study focuses on validating a small scale of 12S-14P outer-rotor hybrid excitation flux switching motor (OR-HEFSM) through simulation, experimental, and mathematical modelling. The JMAG-Designer software as finite element solver is used to design and analyse the designed geometry structure. Throughout simulation process, the rotor design with direct drive structure as illustrated in Appendix A is chosen based on optimisation process. Thus, the generated back EMF, torque, and power through simulation at a speed of 1,200 r/min is 6.58 V, 16.4 Nm, and 12.4 kW, correspondingly. The designed model has been fabricated using actual prototype analysis (APA) approach, which is involves five stages, namely 3-D design, material selection, fabrication, assembly, and experimental test. The computer-aided software of SolidWorks is used to implement the first stage of APA while the prototype structure is fabricated using a computer numerical control (CNC) machine. The prototype has been tested experimentally using a measurement tool such as Fluke Analyser and oscilloscope. The back EMF showed a good agreement between simulation and preliminary experimental results with percentage differences approximately 5.1% at a speed of, 1,200 r/min. In contrast with the prediction results based on mathematical modelling using sizing equation, the calculated back EMF, torque, and power is 7.58%, 8.6%, and 8.4% higher than simulation results, respectively. Even so, the results had proven that the concept of three-phase working principle for small-scale 12S-14P OR-HEFSM with direct drive structure remained the same for simulation, experiment, and prediction.

ABSTRAK

Simulasi, pengujian secara eksperimen dan pemodelan matematik ialah proses penting untuk memberikan bukti yang mencukupi sebelum pembangunan berskala penuh atau pengeluaran secara besar-besaran dilakukan. Oleh itu, kajian ini memberikan tumpuan dalam mengesahkan reka bentuk 12S-14P OR-HEFSM berskala kecil melalui simulasi, eksperimen dan pemodelan matematik. Perisian *JMAG Designer* sebagai penyelesai unsur terbatas telah digunakan untuk mereka bentuk dan menganalisis struktur geometri yang direka bentuk. Melalui keseluruhan proses simulasi, reka bentuk rotor dengan struktur pemacu terus seperti yang ditunjukkan dalam lampiran A telah dipilih berdasarkan proses pengoptimuman. Dengan itu, hasil voltan teraruh, daya kilas dan kuasa melalui simulasi pada kelajuan 1200 r/min masing-masing ialah 6.58 V, 16.4 Nm dan 12.4 kW. Reka bentuk model telah dihasilkan menggunakan pendekatan analisis prototaip (APA) yang melibatkan lima peringkat iaitu reka bentuk 3-D, pemilihan bahan, penghasilan, penyusunan dan kerja pengujian. Perisian berbantukan komputer SolidWorks telah digunakan untuk menerapkan peringkat pertama APA dan prototaip dihasilkan menggunakan mesin kawalan komputer berangka (CNC). Prototaip telah diuji secara eksperimen menggunakan alatan pengukuran seperti *Fluke Analyser* dan osiloskop. Hasil voltan teraruh adalah sepadan dengan hasil simulasi dan eksperimen awal dengan beza peratusan kira-kira 5.1% pada kelajuan 1200 r/min. Berbeza dengan hasil ramalan berdasarkan pemodelan matematik menggunakan persamaan saiz, hasil pengiraan voltan teraruh, daya kilas dan kuasa masing-masing ialah 7.58%, 8.6% dan 8.4% lebih tinggi daripada hasil simulasi. Walau bagaimanapun, hasil ini mengesahkan konsep prinsip kerja tiga fasa untuk struktur pemacu terus 12S-14P OR-HEFSM berskala kecil adalah tetap sama untuk simulasi, pengujian secara eksperimen dan pemodelan matematik.

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LIST OF SYMBOLS AND ABBREVATIONS

A	Ampere
AC	Alternating Current
B	Flux Density [T]
f	Frequency [Hz], [rad/s]
I	Current [A]
J	Current Density [A/m^2]
L	Length [m]
N	Number of turns
P	Number of Poles
S	Slot area [mm^2]
r	Radius [m]
r/min	Revolution Per Minute
T	Torque [Nm]
t	Time [s]
V	Voltage [V]
EMF	Electromotive Force
FEA	Finite Element Analysis
FEC	Field Excitation Coil
FEFSM	Field Excitation Flux Switching Machine or Motor
FSM	Flux Switching Machine or Motor
HEFSM	Hybrid Excitation Flux Switching Machine or Motor
HEV	Hybrid Electrical Vehicles
IMs	Induction Motors
PM	Permanent Magnet
PMFSM	Permanent-Magnet Flux Switching Machine or Motor
SRM	Switched Reluctance Machine or Motor
α	Filling Factor

Kp	Filling Factor Effective Area
Kd	Leakage Factor
Bg / Bpm	Permanent-Magnet Magnetic Flux Density
Rso	Stator Outer Radius
Φ	Magnetic Flux
tr_{AC}	Total Radial Active Component
B	Magnetic Flux Density
Ae	Effective Area
h_{PR}	Rotor Pole Height
DW	Division Weightage
TP	Total Phase
DEM	Division Evaluation Mark
Wfactor	Weightage Factor

LIST OF PUBLICATIONS

Journals

(i) "Actual prototype analysis floor plan for general electric machine," *ARPN Journal of Engineering and Applied Sciences*, Vol. 10, No. 16, pp. 7070-7074.

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LIST OF AWARDS

(i) Silver medal at Malaysia Technology Expo (MTE), International Invention & Innovation, Kuala Lumpur, Malaysia 18 - 20 February 2016.

(ii) Silver medal at Pencipta 2015, Dewan Konvensyen Kuala Lumpur, 4 – 5 December 2015.

(iii) Bronze medal at Seoul International Invention Fair, Korea 26 - 29 November 2015

(iv) Bronze medal at Research & Innovation Festival, UTHM, Malaysia 16 - 17 November, 2015.

(v) Silver medal at Post Graduate Showcase IEEE CENCON 19 – 21 October 2015.

(vi) Silver medal at Poster Competition Hari Transformasi Minda FKEE, UTHM 2015.

(vii) Bronze medal at Malaysia Technology Expo (MTE), International Invention & Innovation, Kuala Lumpur, Malaysia 12 - 14 February 2015.

CHAPTER 1

INTRODUCTION

1.1 Background Introduction

Development of direct-drive motor for in-wheel electric vehicle (EV) has grown into an interesting research topic because of their advantages of direct torque control and elimination of the transmission gear system. At present, the major types of electric motors under serious consideration for EVs are the DC motor, induction motor (IM), permanent magnet synchronous motor (PMSM), and switched reluctance motor (SRM) [1,2]. Based on the extensive review on state-of-the-art electric propulsion systems, it may be observed that investigations on cage IMs and PMSMs are highly dominant [3-5].

In fact, from various types of motors, the flux switching motor (FSM) is a good design to fulfil direct-drive application due to high starting torque, constant power over a wide speed range, low torque ripple, and high durability. The FSM operating principle is quite interesting. This is due to the flux switches from stator pole to rotor tooth and vice versa that made researchers to develop a novel FSM design for various applications ranging from domestic appliances to heavy applications such as electric traction [6, 7].

The outer-rotor hybrid excitation flux switching motor (OR-HEFSM) [8, 9] is one of the FSMs created and studied to fulfil future expectations of electric vehicles (EV) with more practical application. In this research, the development of small scale 12S-14P OR-HEFSM is guided by a full-scale 12S-14P OR-HEFSM design, which has been published and submitted for patent [10]. Moreover, the full-scale design has successfully achieved the target values and has overcome various problems in interior permanent magnet synchronous machine (IPMSM) used in EV. The full-scale 12S-

14P OR-HEFSM design generated torque and power of 335.08 Nm and 160.2 kW, respectively [11].

Theoretically, the design capability has been proven through finite element analysis (FEA) using computer-aided software, JMAG designer. Basically, the analysis is based on numerical input and operating principle without any compromise towards error factor from manufacturing such as mechanical deformation. Therefore, development and fabrication process are required to evaluate the motor performance through prototype units [12]. However, because of cost and tool constraints, the design dimension and volume have been rescaled by ratio 1:8.

To interpret the outer-rotor design into prototype unit, the design needs a few approaches to complete the whole process such as actual prototype analysis (APA) and FEA-based simulation. The APA is created to set a standard procedure to develop and fabricate the design via five stages – design, material selection, fabrication, assembly, and test. All stages of APA come with a specific objective to initiate the process guided by closed loop flow chart to reach high standards in fabrication. Through the last stage of APA, the experimental test has been conducted to finalise all aims in the development and fabrication process [13].

1.2 Problem Statement

In recent research of electric motor drives for EV propulsion, in-wheel direct drive is becoming more popular in diminishing transmission gearing system, and available cabin space can be occupied by more batteries. Thus, this application does not only provide optimal torque directly to the wheel, but also contributes for light vehicle and wider driving range per charge. In considering for higher torque and power densities for the in-wheel drive motors, outer-rotor machine configuration is among the good designs compared with conventional inner-rotor [11].

In a recent review of motor design especially FSM, most researchers focused on designing the motor using computer-aided software, but which lack of experimental prototype validation because of cost and measurement tool restriction. As an example, a 12S-14P OR-HEFSM has been successfully design for in-wheel direct drive application. The performances achieved in terms of torque, speed, and power are much higher than conventional IPMSM [10]. The design has successfully countered IPMSM’s drawbacks with robust rotor structure, less PM usage, and less total weight.

However, the proposed motor is yet to be validated experimentally. Thus, in this research, a complete process involving design and fabrication of a small-scale 12S-14P OR-HEFSM shall be carried out from the initial stage to the end of experimental validation before it goes for full scale or mass production.

1.3 Objectives

The objectives of this research are as follows:

(i) To optimise and analyse a small-scale design of 12S-14P OR-HEFSM rotor for direct drive structure.

(ii) To develop and fabricate a small-scale design of 12S-14P OR-HEFSM using actual prototype analysis (APA).

(iii) To validate a small-scale design of 12S-14P OR-HEFSM by analytical modelling and experimentation.

1.4 Scopes

The research focuses on optimising and analysing a small-scale prototype of three-phase 12S-14P OR-HEFSM, which will be evaluated by analytical modelling and experimentation. In achieving the research objectives, the followings scopes have been selected:

(i) Guided by a full-scale design of 12S-14P ORHEFSM [11], the design restriction and specification for a designated small-scale design of 12S-14P OR-HEFSM by a ratio of 1:8 are listed in Table 1.1. The FEA process is aided by JMAG Designer 14 software to design and analyse the load and no load conditions.

(ii) In developing the small-scale prototype of 12S-14P OR-HEFSM, the APA approach is used. The approach uses a conversion import file format .DWG from JMAG-Designer to .SLDPRT for SolidWorks V.2014. The 2-D projection from JMAG-Geometry will be 'boss extruded' into SolidWorks to generate the 3-D projection.

(iii) Using the motor measurement system, the finishing prototype will be evaluated by Power Flux and Futex Sensit for back EMF and cogging torque, respectively. The investigated data will be compared with simulation and analytical modelling data to prove the concept of three-phase motor characteristics.

(iv) In determining whether the APA approach is acceptable for general electric motor fabrication, the collected data of simulation analysis and five stages of APA will be evaluated using subjective evaluation method [14]. The evaluation uses numeric score as weightage factor based on data feedback from motor performance and fabrication qualities.

Table 1.1: Restriction and specification

RESTRICTION AND SPECIFICATION	DESCRIPTION	OR-HEFSM
Electric	Max. DC-bus voltage inverter (V)	400
	Max. DC-bus voltage inverter (V)	400
	Max. inverter current (A_{rms})	50
	Max. current density in armature coil, Ja (A_{rms}/mm^2)	30
	Max. current density in FEC, Je (A/mm^2)	30
Motor	Motor radius (mm)	66
	Motor stack length (mm)	35
	Shaft/Inner motor radius (mm)	30
	Air gap length (mm)	0.4
	PM weight (g)	17
	Total weight (kg)	10

1.5 Research Contribution

Research contribution throughout this research study are described as follows:

(i) The rotor optimisation and analysis of a small-scale design of 12S-14P OR-HEFSM contributed to the idea on how the rotor design should be developed to suit with direct drive structure. Simultaneously, presenting the analysis of a small-scale 12S-14P OR-HEFSM in terms of back EMF, torque, speed, and power. (Structural and assembly design of outer-rotor hybrid excitation flux switching motor based on finite element analysis approach published in *Energy Conversion (CENCON), 2015 IEEE Conference*)

(ii) The APA approach contributes to the systematic flowchart to develop and fabricate the electric motor. Moreover, the APA weightage factor could be used to determine the successfulness of the fabricated prototype. (Actual prototype analysis floor plan for general electric machine, published in *ARPN Journal of Engineering and Applied Sciences*)

(iii) The mathematical modelling for OR-HEFSM using analytical sizing equation contributes to the motor performances prediction in terms of power and torque.

(iv) The three-phase fabricated small-scale 12S-14P OR-HEFSM working principle has been proven experimentally.

1.6 Thesis Outline

This thesis deals with the design studies on OR-HEFSM for HEV applications. The thesis is divided into five chapters. A summary of each chapter is as follows:

(i) Chapter 1: Introduction

This chapter introduces the research background of design and development of a small-scale 12S-14P OR-HEFSM. The contents focus on problems, objectives, scopes, and contributions of the research.

(ii) Chapter 2: Literature review

The review on developing and fabricating the 12S-14P ORHEFSM was divided into three sections. The first section is the introduction of flux switching motor (FSM) while focusing on hybrid excitation FSM. It is followed by the review of fabrication process, which is already established and used by other researchers. The review covers both motor concepts, from inner to outer rotor fabrication. At the end of the chapter is the review of measurement systems and weightage for experimental purpose.

(iii) Chapter 3: Design and analysis of small-scale 12S-14P OR-HEFSM using JMAG-Designer

This chapter presents the process before the prototype's development. The process involves the rotor optimisation and simulation process for small-scale 12S-14P OR-HEFSM using JMAG-Designer. Although the performances of a small-scale design is quite different from a full-scale analysis, the results proved that the concept of three-phase working principle concept for both designs remained the same.

(iv) Chapter 4: Prototype development of the designed 12S-14P OR-HEFSM using APA

This chapter clarifies the complete process and results based on the second research objective. It is divided into three sections namely development of APA approach, development of small-scale prototype, and development of direct drive prototype. The development of small scale and direct drive prototype has been developed by four stages of APA from 3-D design, material selection, fabrication, and assembly.

(v) Chapter 5: Experimental analysis of a small-scale prototype

This chapter elaborates the experimental analysis of a small-scale prototype of 12-14P OR-HEFSM with respect to simulation configuration. The tool and calculation process have been explained based on analysis. The analysis is divided into three sections namely experimental analysis for no load condition, prediction motor performances based on analytical sizing equation, and weightage analysis.

(vi) Chapter 6: Conclusion and future work

The final chapter discusses and concludes the process and results of the research. This chapter also suggests future works to eliminate the drawbacks in small-scale prototype development.

CHAPTER 2

LITERATURE REVIEW

2.1 Flux Switching Motor

The flux switching motor (FSM) incorporates the features of a conventional DC motor and switch reluctance motor (SRM). Similar with conventional motor, the rotor and stator combinations of FSM play a role to drive their operating principle as well as coming out with various designs probability. In 1950, the first FSM was introduced. Structurally it had a large value of permanent magnet usage with less slot area [15]. To overcome the large value of permanent magnet usage and to improve the FSM structure topologies, researchers have tried to figure out the best combination of FSM in terms of the stator-rotor structure and excitation component.

The general classification of FSMs is demonstrated in Figure 2.1, where the permanent magnet (PM) and field excitation (FE) FSMs consist of PM and DC field excitation coil, respectively as their excitation element. The hybrid excitation (HE) FSM consists of the combination of both PM and FE for their flux excitation.

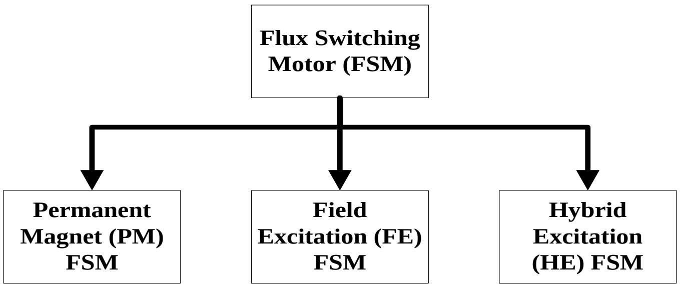

Figure 2.1: Classification of flux switching motor (FSM)

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