DESIGN OF COMPACT MODULAR ROTOR PERMANENT MAGNET FLUX SWITCHING MACHINE FOR ELECTRIC VEHICLES

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To my beloved mother and father

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ABSTRACT

Permanent magnet flux switching machines (PMFSM) have attracted considerable interest in recent years. Amongst all designs, AlCiRaF PMFSM with salient rotor has been introduced for electric vehicle applications. Although it has less PM volume and less flux leakage, the torque and power performance can still achieve 47 Nm and 11 kW, respectively, higher than the conventional C-core 12S-10P PMFSM. However, the salient rotor and stator of PMFSM with single-tooth winding have inherited longer flux paths and high iron losses, affecting the motor's torque and efficiency. In this research a modular rotor PMFSM with higher flux linkage is proposed and design using 2D finite element analysis (2D-FEA) JMAG designer software version 18.1. The Deterministic Optimization Method (DOM) is executed by treating sensitive design parameters defined in the rotor segments, stator, armature slot and PM to improve the motor's performance. Consequently, the optimized design has 20% better flux linkage compared to initial design along with 39.89%, 60% and 6% increments in torque, power, and efficiency respectively. Moreover, flux linkage and torque characteristics analysis of the proposed design are examined and compared with existing sandwich PMFSM topologies under similar dimensions. Accordingly, the optimized PMFSM modular rotor can achieve improved torque and power values of 57.29 Nm and 23.23 kW, respectively, which are higher than the target values. Thus, sizing optimization technique has been employed by altering the stator outer radius and stack length until the target torque and power of 47 Nm and 11 kW are achieved. As a result, the motor size has been reduced to 0.86 kg, which is 10.39% from the initial size. It can be concluded that the proposed PMFSM modular rotor PMFSM and compact modular rotor PMFSM have shown promising capabilities to achieve higher torque and power at maximum speed ranges.

ABSTRAK

Mesin pensuisan fluks magnet kekal (PMFSM) telah menarik perhatian yang besar sejak beberapa tahun kebelakangan ini. Antara semua reka bentuk, AlCiRaF PMFSM dengan rotor menonjol telah dipilih untuk diperkenalkan bagi aplikasi kenderaan elektrik. Walaupun ia mempunyai kurang kelantangan PM dan kebocoran fluks, tork dan prestasi kuasa masih boleh mencapai 47 Nm dan 11 kW, lebih tinggi daripada teras konvensional C 12S-10P PMFSM. Walau bagaimanapun, rotor dan pemegun menonjol PMFSM dengan belitan gigi tunggal mempunyai laluan fluks yang lebih panjang dan kehilangan besi yang tinggi yang boleh menjejaskan tork dan kecekapan motor. Dalam penyelidikan ini, rotor PMFSM modular dengan pautan fluks yang lebih tinggi telah dicadangkan dan direka bentuk menggunakan analisis unsur terhingga 2D (2D-FEA) perisian pereka JMAG versi 18.1. Kaedah pengoptimuman deterministik telah dilaksanakan dengan pembaikan parameter reka bentuk sensitif yang ditakrifkan dalam segmen rotor, pemegun, slot armatur dan PM untuk meningkatkan prestasi motor. Dengan itu, reka bentuk yang telah dioptimumkan mancapai pautan fluks 20% lebih baik berbanding dengan reka bentuk awal bersama dengan kenaikan 39.89%, 60% dan 6% masing-masing dalam tork, kuasa dan kecekapan. Selain itu, analisis pautan fluks dan ciri tork dalam reka bentuk yang dicadangkan telah diperiksa dan dibandingkan dengan topologi sandwic PMFSM sedia ada dengan dimensi yang sama. Sehubungan itu, rotor modular PMFSM yang dioptimumkan boleh mencapai nilai tork dan kuasa yang lebih baik dengan nilai 57.29 Nm dan 23.23 kW, lebih tinggi daripada nilai sasaran. Oleh itu, teknik pengoptimuman pensaizan telah digunakan dengan mengubah jejari luar pemegun dan panjang tindanan sehingga sasaran tork dan kuasa bernilai 47 Nm dan 11 kW dicapai. Hasilnya, saiz motor telah dikurangkan kepada 0.86 kg, iaitu 10.39% daripada saiz awal. Dapat disimpulkan bahawa cadangan rotor modular PMFSM dan rotor modular padat PMFSM telah menunjukkan keupayaan yang menjanjikan tork dan kuasa yang lebih tinggi pada julat kelajuan maksimum.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of study

It is noticeable that using electric machines (EMs) is significant for the advancement of our world, economically and environmentally for innovative development. As a result, substantial progress has been made in enhancing the performance of electric motors to make them appropriate for automotive and aerospace applications. These improvements are in the aspect of torque, power, efficiency, speed range, reliability, and controllability [1-3]. The requirement for automotive applications includes high torque, high efficiency, high precision, less heat loss, less weight, little use of start-up energy and less vibration. Thus, high torque motors are used for automotive applications such as light weight fully electric vehicle (FEV) [4-8]. EM provides torque and speed for applications and has proven to be a core component in this development and transformation process [9-11]. The torque of EM determines its performance and category of applications therefore, research for high torque motors is crucially significant for sustainable applications. The latest research and development have made possible many in-wheel automotive applications to be equipped with high torque electric motors [12,13].

Permanent magnet synchronous motor (PMSM) is used for automotive applications due to its predominant magnetic properties such as high torque density, high torque, high efficiency, wide speed range and maintenance free operation but it locates active materials on the rotor [14-17]. The disadvantages of PMSM include PM volume, limited field weakening capability, reduced slot surface area and high heat loss [18-20].

In another developments, flux switching motor (FSM) is an advanced form of synchronous motor (SM) built by combining the structures of switched reluctance machine and inductor alternator with no active material located on the rotor [21-23]. FSMs can be categorized into three types by the nature of their excitation used, such that permanent magnet (PM) FSM, field excitation (FE) FSM and hybrid excitation (HE) FSM. In PMFSM and FEFSM main excitation sources used are PM and FE correspondingly, while both PM and FE are combined to generate flux in HEFSM [24]. Due to its construction and characteristics, FSM has the advantages of less material usage, light weight, and speed operation. Characteristically, FSM operates with a double electrical frequency and has attracted researchers' interest around the world [25-28].

Over the years, PMFSMs have won a significant amount of share in today's researchers' studies due to their considerable advantages of free loss excitation [29-31]. Due to the advancement of modern high-performance rare earth magnetic materials, PMFSMs are being increasingly more popular in various applications, ranging from electric and hybrid electric vehicles, renewable energy systems including wind power generators, electric aircrafts, industrial drives, automations, to domestic appliances. [32, 33].

It has been defined that, HEV and EV applications require electric motor with characteristics such as: 1) high power and torque density; 2) high overload torque; 3) wide speed range; 4) high efficiency over wide torque and speed range; 5) wide constant power range; 6) reliable and robust; 7) low noise and vibration; 8) low cost. In the current marketed products, IPM motors are the dominant. Multi-layer IPM motor is employed in the BMW i-series plug-in EVs, whereas V-shaped IPM motor is used in Toyota Prius and Camry EVs. Moreover, IPM motors are used in Nissan Leaf and Ford Focus EVs without any further information published regarding their specification. On the other hand, the classical induction motor issued by Tesla Motors Inc. in all their products; they refer to their electric induction motors as copper rotor motor in order to distinguish it from the motors with PMs in the rotors [140-142].

PMFSM with salient rotor has a better ability in field weakening than conventional PM motors because the excitation field is parallel to the field generated by the armature winding [17 – 19]. PMFSM motors have significant fault tolerance behavior and stability as well [22]. Additionally, the flux linkages of these motors are naturally bipolar, resulting in a solely sinusoidal back-EMF and fewer harmonics.

[20]. However, salient rotor structure is found to lead a longer magnetic flux path between stator and rotor producing weak flux linkage along with low torque performances [23–25]. To overcome some of these drawbacks, a segmented PMFSM topology with an inner rotor is proposed in [20]. In comparison with conventional motors, the magnetic flux path is shorter, and the direct coupling of the coil flux to the segments results in higher torque density, reduction in copper consumption, lower PM consumption as well as copper losses.

1.2 Problem statement

The permanent magnet flux switching (PMFSM) machines have gained wide application from aerospace to automobile industries since they offer several key advantages, such as simple and robust rotor, short end winding, high torque density, high efficiency, excellent flux-weakening capability, etc. Various PMFSM topologies have been emerged since its operation principle was firstly introduced [17,18,24]. Their torque performance generated by interaction between armature and PMs have been widely designed and developed for various applications. One of the typical PMFSM topologies which are often investigated is the 12/10-stator/rotor-pole PMFSM where one permanent magnet (PM) piece is located in each stator pole. The conventional design is, however, receive the drawbacks of high PM volume. Hence, variety of PMFSM designs has been introduced ever since. For reducing the number of PM consumption, the stator poles are substituted alternately by a simple stator tooth and consequently the new E-core is established [13]. Recently another design is established in PM with alternate circumferential and radial direction [15,16] but there are some drawbacks of alternate circumferential and radial (AlCiRaF) PMFSM that reduce the torque and efficiency of the motor, such as flux cancellation, longer flux paths and flux leakage. In the Figure 1.1, blue circle shows the areas where fluxes are cancelled due to opposite fluxes produced by the radial and circumferential source pattern. However, the salient rotor structure is found to lead a longer magnetic flux path between stator and rotor producing weak flux linkage along with low torque performances is illustrated in Figure 1.1. In addition, weight of the motor is an important factor to keep in consideration in PMFSM designs, as it directly affects the efficiency, structural integrity, manufacturing, installation, and thermal management.

Therefore, considering these issues, a compact modular rotor PMFSM topology is proposed to comprehensively improve motor performance, including torque density, efficiency, and optimized weight.

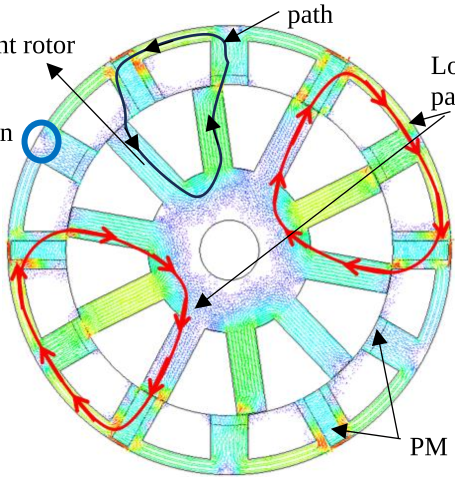

Figure 1.1: Flux cancellation and longer flux paths in AlCiRaF PMFSM

1.3 Aim and objectives of study

The main objective of this research is to develop a modular rotor permanent magnet flux switching motor for electric vehicle applications. In achieving the main objective, there are some specific objectives that have to be fulfilled, which are

(i) To design the proposed modular rotor PMFSM motor in order to reduce the longer flux path in rotor.

(ii) To analyse three different topologies of Sandwich PM modular rotor using same dimensions for flux linkages and torque performance.

(iii) To optimize the weight of the motor of the proposed motor by using sizing optimization technique for electric vehicles.

1.4 Scope of the study

To conduct this research, commercial JMAG designer version 18.1 released by Japan Research Institute (JRI) is used as 2D-FEA solver to investigate the motor's performance. The proposed modular rotor PMFSM structure is designed following IEC standard (IEC 60034-1) which is (Rotating electrical machines – Part 1: Rating and performance) [32]. The scope of this research is emphasized on the following points.

(i) Initially, a coil test analysis was performed for feasible topologies of PMFSMs to confirm the operating principle of proposed modular rotor PMFSM.

(ii) The limit of the current density was set to the maximum at 30 A_{rms}/mm^2 for armature winding. Which is similar as AlCiRaF PMFSM [33-34] for electric vehicles along with the same outer diameter, stack length and air gap following the IEC standard "IEC 60034-22:2009". Therefore, the design parameters and specification of AlCiRaF PMFSM for electric vehicles are displayed in Table 1.1.

(iii) The electromagnetic performance of proposed modular rotor PMFSM, including induced EMF, cogging torque, and average torque is analysed and compared with various PM sandwiched FSM using 2D-FEA. The torque-speed characteristics were evaluated by varying the armature phase angle, θ.

(iv) Deterministic optimization approach (DOA) is used to achieve optimum average torque and power for proposed modular rotor PMFSM. The outer diameter of stator, the motor stack length, the shaft radius, and the air gap, having dimensions of 150 mm, 70 mm, 30 mm and 0.5 mm, respectively, are kept constant during the various cycles of optimization.

(v) In this research, certain aspects, namely costing, thermal expansion, cooling system, noise and vibrations, environmental impact, electromagnetic interference (EMI), and mechanical stresses, were not covered.

Table 1.1: Design restrictions and parameters of AlCiRaF PMFSM [34]

Items	Units	AlCiRaF PMFSM
Stator outer diameter	mm	150
Rotor outer diameter	mm	55
Rotor inner diameter	mm	20
Motor stack length	mm	70
Air gap	mm	0.3
Shaft diameter	mm	20
PM weight	kg	0.50
Maximum armature current density (Ja)	A_{rms}/mm^2	30
Number of turns (N)	-	42

1.5 Contribution to Knowledge

The contributions of this research are as follows:

(i) Utilizing 0.35kg weight of PM and 50% number used in AlCiRaF PMFSM motors, the 6S/10P modular rotor PMFSM achieved a high average torque of 57.29Nm. this torque performance is higher than AlCiRaF PMFSM by 21.37%. in terms of losses, the proposed design has produced less iron loss and copper loss.

(ii) Deterministic optimization method (DOM) was adopted to improve the motor characteristics and compared with the existing designs of PMFSMs. The optimized design has achieved better characteristics than the existing designs and published.

(iii) Various configurations of sandwich PMFSM with different rotor numbers and 6 stator slots have been reviewed and published in journals.

(iv) Sizing optimization technique is employed to reduce the weight and average torque of the optimized modular rotor PMFSM for electric vehicles.

1.6 Thesis outline

This thesis deals with the design investigation, optimization, and comparison of modular rotor PMFSM and PM sandwich PMFSM for electric vehicle applications. This is structured into five chapters and the summary of each chapter are listed as follows:

(i) Chapter 2: Literature Review

This chapter explains the literature on electrical motors and the classification of flux switching motors, and a critical review discusses various existing designs of PMFSM. Furthermore, literature on optimization is also highlighted in this chapter.

(ii) Chapter 3: Methodology

This chapter describes the project implementation of this research. The project implementation is divided into three stages including design, analysis and optimization of proposed modular rotor PMFSM in terms of flux linkage, secondly, comparison of various modular rotor PM sandwich PMFSM with proposed modular rotor PMFSM and thirdly, the process of reducing weight of the proposed design using sizing optimization technique to obtain the target torque of 47Nm and power of 11 kW.

(iii) Chapter 4: Results and analysis

This chapter comprises outcomes of the research, including design examination, performance analysis and optimization process. Initially, the design investigation and performance improvement of proposed modular rotor PMFSM have been presented based on FEA and deterministic optimization method. The proposed design is compared with three other modular rotor PM sandwich PMFSM designs. This chapter concludes by demonstrating that the weight optimization of the proposed modular rotor PMFSM is compacted using the sizing optimization technique to accomplish the target torque and power values.

(iv) Chapter 5: Conclusion

The final chapter presents a comprehensive summary of the research findings and includes a comparative analysis with previous work. It identifies potential areas for future research to further enhance the design.

CHAPTER 2

OVERVIEW OF FLUX SWITCHING MOTORS

2.1 Introduction

This chapter reviews the application and the design of flux switching machines (FSMs) in electric vehicles and the variation in FSM designs to achieve enhanced performance. In comparison with the closely related switched reluctance machine (SRM), the FSM is considered to offer added advantages such as higher torque density [26], high-speed capability [27], low vibration [28] and acoustic noise [29]. FSMs can be designed for high output torque, high speed, ease of control and relatively low-intensity vibration [28,30].

FSMs may have a permanent magnet (PM) excitation, a Field excitation (FE) or hybrid excitation (combines both PM and FE). FSMs with PM excitation achieve high torque density; however, they may not be capable of extended speed operation due to voltage limitations. By incorporating FE, extended speed operation has been demonstrated in [31].

FSMs have a fault-tolerant capability under phase faults, which meet requirements of system reliability in safety critical applications. The rotor of an FSM has a robust structure without winding or any PM material. As the PMs are located on the stator, the temperature rise of the magnets can be controlled easily. These features enable FSMs to be applied in transportation, renewable energy, and aerospace applications. The two rotor configurations used in electric motors are inner rotor and outer rotor. The two rotor types are salient rotor and segmented/modular rotor. Both structures of motor design are presented and discussed. The performances of all the motors are presented in detail with merits and demerits. FSM which has three types with the two rotor configurations are presented and discussed. Finally, the research

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APPENDIX A

LIST OF PUBLICATIONS

(a) Journals

1. **Irfan Ali Soomro**, Erwan Sulaiman, Mohd Fairoz Bin Omar & MD Zarafi Bin Ahmad "Design Optimization Methods for Electrical Machines: A Review, *Journal of Electrical Engineering & Technology*, 2022. **(ISI, Q4, IF:1.569)**

2. **Irfan Ali Soomro**, Erwan Sulaiman, & Roziah Aziz, Performance analysis and comparison for various excitation source salient rotor with modular rotor permanent magnet of flux switching machine", *Journal of Electrical Engineering & Technology*, 2022. **(ISI, Q4, IF:1.569)**

3. **Irfan Ali Soomro**, Erwan Sulaiman, Mahyuzie Jenal & MD Zarafi Bin Ahmad "Performance improvement of modular rotor flux switching machine using deterministic technique, *Ain Shams Engineering Journal* 2023. (Under Review)

(b) Proceedings

1. **Irfan Ali Soomro**, Erwan Bin Sulaiman, Mahyuzie Bin Jenal, MD Zarafi Bin Ahmad, Nur Afiqah Binti Mostaman, Design of 6 slots/10 poles modular rotor sandwich switched flux switching permanent magnet motor. 6^{th} International Conference on Clean Energy and Technology Conference (CEAT). 7^{th} – 8^{th} June 2023.

2. **Irfan Ali Soomro**, Erwan Bin Sulaiman, Mahyuzie Bin Jenal, MD Zarafi Bin Ahmad, Nur Afiqah Binti Mostaman, Performance analysis of V-shape magnets sandwich switched flux switching permanent magnet motor using modular rotor. 6^{th} International Conference on Clean Energy and Technology Conference (CEAT). 7^{th} – 8^{th} June 2023.

3. **Irfan Ali Soomro**, Erwan Bin Sulaiman, Mahyuzie Bin Jenal, MD Zarafi Bin Ahmad, Nur Afiqah Binti Mostaman, Performance Comparison of Conventional and V-Shape Magnets Sandwich Flux-Switching Permanent Magnet Machines with Modular Rotor Topology. 7^{th} International Conference on Electrical, Control and Computer Engineering (InECCE). 22^{nd} August 2023.

4. **Irfan Ali Soomro**, Erwan Bin Sulaiman, Mahyuzie Bin Jenal, MD Zarafi Bin Ahmad, Nur Afiqah Binti Mostaman, Design of V-Shape Magnets Sandwich Flux-Switching Permanent Magnet Machines with Modular Rotor Topology. 7^{th} International Conference on Electrical, Control and Computer Engineering (InECCE). 22^{nd} August 2023.

5. **Irfan Ali Soomro**, Erwan Sulaiman, Mahyuzie Jenal and MD Zarafi Ahmed, Electromagnetic performance of sandwich permanent magnet flux-switching machine using modular rotor. International Postgraduate Conference for Energy Research (IPCER) 2022

6. **Irfan Ali Soomro**, Erwan Sulaiman, Roziah Aziz and MD Zarafi Ahmed, Magnetic Flux Characteristic of Modular rotor Based Permanent Magnet Flux Switching. International Conference on Electrical and Electronic Engineering 2021 (ICon3E 2021).

APPENDIX B

VITA

The author was born on 7th April 1985, in Nawabshah Sindh, Pakistan. He graduated from Quaid-e-Awam University of Engineering, Science and Technology (QUEST), Nawabshah, Sindh Pakistan in Electrical Engineering in 2007. In 2008, he started working as lecturer in the Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh Pakistan. He taught Basic Electrical Engineering, Instrumentation & Measurements and Basic Electronic Engineering during his working period at QUEST Nawabshah. Pakistan