A NEW THREE PHASE 6-SLOTS 10-POLES PERMANENT MAGNET FLUX SWITCHING MACHINE WITH INNER ROTOR CONFIGURATION

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Dedicated to

my beloved family,

my siblings and my friends

who always encouraged me with their loves and prayers.

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ABSTRACT

Effective use of energy permits industrial and commercial facilities to cut down production costs, boost profits, and stay competitive. Also, the majority of electrical energy consumed in most industrial facilities is used to run electric motors. There has been a recent interest in flux switching motor (FSM) in which all flux sources are stalled in the stator that makes the rotor simple, robust, and brushless. Development of current research, particularly in conventional permanent magnet flux switching machine (PMFSM) has been with toothed rotor structures that employ permanent magnet at the stator that may manipulate the changes of paths for the stator teeth. Still this structure produces less torque and power. Hence, the use of multiple rotor structures has been developed, along with proposed PM configurations, which give significant gains. This research work focused on a new design of PMFSM employing alternate circumferential and radial flux (AlCiRaF) permanent magnet over various rotor poles configuration, optimization based on deterministic method and performance investigation through 2D-FEA. In this work, four topologies have been proposed, such as 6S-10P PMFSM with salient type of rotor (SalR), 6S-10P PMFSM with span rotor (SpR), 6S-8P AlCiRaF PMFSM with segmental rotor (SegR AlCIRaF) and 6S-10P AlCiRaF PMFSM with salient rotor (SalR AlCiRaF) are modeled and simulated using 2D-FEA JMAG v. 14.1 for the initial performance investigation. Since, 6S-10P SalR AlCiRaF has shown higher tendency to achieve better performances compared to conventional design, the model is then undergo further refinement through deterministic optimization method by shifting modeling free parameters in rotor and stator part. Finally, 6S-10P AlCiRaF has achieved better torque, power, speed ranges and efficiency compared with conventional 12Slot-10Pole PMFSM. Besides the optimized 6S-10P AlCiRaF has improved approximately 85.71% of maximum torque and 156% of maximum power than that of initial design machine proving their suitability towards efficient and reliable motors.

ABSTRAK

Penggunaan tenaga yang berkesan membolehkan kemudahan perindustrian dan komersil untuk mengurangkan kos pengeluaran, meningkatkan keuntungan dan kekal berdaya saing. Di samping itu, kebanyakan tenaga elektrik yang digunakan di kebanyakan kemudahan perindustrian digunakan untuk menjalankan motor elektrik. Baru-baru ini, terdapat minat yang baru-baru ini dalam mesin pensuisan fluks (FSM) di mana semua sumber fluks di pemegun telah menjadikan pemutar lebih mudah, teguh dan tanpa berus. Pembangunan penyelidikan semasa terutamanya dalam mesin konvensional pensuisan fluks magnet (PMFSM) dengan struktur pemutar bergigi yang menggunakan magnet kekal di pemegun yang boleh memanipulasi perubahan laluan fluks pada gigi pemegun tetapi struktur ini menghasilkan kurang tork dan kuasa. Oleh itu, penggunaan pelbagai struktur pemutar telah dibangunkan, bersama-sama dengan konfigurasi magnet kekal (PM) yang dicadangkan dimana memberi kelebihan yang ketara. Kerja penyelidikan ini tertumpu pada rekaan baru PMFSM dengan menggunakan magnet tetap lilitan dan aliran fluks (AlCiRaF) terhadap pelbagai konfigurasi kutub rotor, pengoptimuman berdasarkan kaedah deterministik dan penyiasatan prestasi melalui 2D-FEA. Terdapat empat topologi yang dicadangkan, 6S-10P PMFSM dengan jenis pemutar salient (SalR), 6S-10P PMFSM dengan rotor span (SpR), 6S-8P AlCiRaF PMFSM dengan rotor segmen (SegR AlCIRaF) dan 6S-10P AlCiRaF PMFSM pemutar (SalR AlCiRaF) dimodelkan dan disimulasikan menggunakan 2M-FEA JMAG v. 14.1 bagi penyiasatan prestasi awal. Oleh kerana 6S-10P SalR AlCiRaF telah menunjukkan kecenderungan yang lebih tinggi untuk mencapai prestasi yang lebih baik berbanding dengan reka bentuk konvensional, model itu kemudian menjalani penambahbaikan selanjutnya melalui kaedah pengoptimalan deterministik dengan mengubahsuai parameter bebas pemodelan di bahagian pemutar dan pemegun. Akhirnya, 6S-10P AlCiRaF telah mencapai tork, kuasa, julat kelajuan dan kecekapan yang lebih baik berbanding mesin konsional 12Slot-10Pole PMFSM. Di samping itu, 6S-10P AlCiRaF yang optimum telah meningkatkan kira-kira 85.71% tork maksimum dan 156% kuasa maksimum daripada

mesin reka bentuk awal membuktikan kesesuaian mereka terhadap motor yang cekap dan boleh dipercayai.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A_g	-	Air gap
A_w	-	Area of wire
α	-	Filling factor
B	-	Magnetic field
E_B	-	Bottom end coil length
E_{ind}	-	The voltage induced in the turn of the coil
E_T	-	Top end coil length
e_k	-	Phase back-emf
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
H	-	Stack length
I_a	-	Armature coil current
I_e	-	Field excitation coil current
i_k	-	Phase current
J_a	-	Armature current density
J_e	-	Field current density
k	-	Phase designation
L	-	Length of 1 turn
L_k	-	Phase winding inductance
L_{si}	-	Circumference of the inner stator
m	-	Natural number
η	-	Efficiency
N	-	Number of turns of wire in coil
N_{cte}	-	Electrical angle of rotation for each period of cogging torque
N_{ctp}	-	Number of periods
N_e	-	Number of FE coils

N_r	-	Number of rotor poles
N_s	-	Number of stator slots
n_s	-	Rotational speed in revolution per minute
P	-	Instantaneous power
P_{ac}	-	Armature coil copper loss
P_c	-	Copper loss
P_{fec}	-	FEC copper loss
P_i	-	Iron loss
P_o	-	Output power
P_r	-	Rotor iron loss
P_s	-	Stator iron loss
R	-	Resistance
r_{ir}	-	Inner radius of the rotor
r_{or}	-	Outer radius of the rotor
r_{sbi}	-	Radius of stator back inner
r_{si}	-	Inner radius of the stator
r_{so}	-	Outer radius of the stator
S_e	-	FEC slot area
S_a	-	Armature coil slot area
t	-	Time
T_e	-	Electromagnetic torque
T_{rel}	-	Reluctance torque
T_{exc}	-	Excitation torque
w_r	-	Rotor tooth width
w_s	-	Stator tooth width
ω_r	-	Rotational speed in radian per second
θ	-	Electrical angular position of the rotor
θ_{seg}	-	Segmental rotor span
ρ	-	Copper resistivity
φ	-	Flux
Ψ_{exc}	-	Flux linkage due to field excitation
ABC	-	Artificial Bee Colony
ACW	-	Anti-clockwise

AFPMSM	-	Axial flux permanent magnet machine
AlCiRaF	-	Alternate circumferencial and radial Flux directions
ASMA	-	Artificial bee colony-strength Pareto and evolutionary algorithm
CAD	-	Computer aided design
CGA	-	Conjugate gradient algorithm
CNC	-	Computer numerical control
CW	-	Clockwise
DC	-	Direct current
DE	-	Differential evolution
DFDSM	-	Doubly fed dual stator motor
DOM	-	Deterministic optimization method
Dy	-	Dysprosium
EA	-	Evolutionary algorithm
EDA	-	Estimation of distribution algorithm
EV	-	Electric vehicle
FE	-	Field excitation
FEA	-	Finite element analysis
FEFSM	-	Field excitation flux switching motor
FEM	-	Finite element method
FEC	-	Field excitation coil
FSM	-	Flux switching motor
GA	-	Genetic algorithm
GBA	-	Gradient based algorithm
HCF	-	Highest common factor
HE	-	Hybrid excitation
HEFSM	-	Hybrid excitation flux switching motor
IM	-	Induction motor
IOA	-	Intelligent optimization algorithm
IPMSM	-	Interior permanent magnet synchronous motor
MOA	-	Multi-objective algorithm
Nd	-	Neodymium
NSGA	-	Non-dominated sorting genetic algorithm
PM	-	Permanent magnet
PMFSM	-	Permanent magnet flux switching motor

PMSG	-	Permanent magnet synchronous generator
PMSM	-	Permanent magnet synchronous motor
PSO	-	Particle swarm optimization
RS	-	Response surface
SalR	-	Salient Rotor
SpR	-	Spin rotor structure
SegR	-	Segmental rotor structure
SPEA	-	Strength Pareto evolutionary algorithm
SQP	-	Sequential quadratic programming
SRM	-	Switched reluctance motors
THD	-	Total harmonic distortion
TM	-	Taguchi method
TS	-	Tabu search
WA	-	Winding arrangements

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

The world in the 21st century today saw how the issue of global warming is a major concern by the public. Therefore, many extensive studies have been carried out by certain parties to prove that this is not an isolated issue that needs to underestimate but instead to come out with series of factor findings, promising proposals, and feasible solutions [1-5]. As reported in [1-2], one of the major factors in worsening global warming is the emission of human-made greenhouse gases (GHGs). Where carbon dioxide (CO_2) is identified as one of the major GHG released into the atmosphere by the combustion of fossil fuel [3].

The conventional internal combustion engine (ICE) has been used in vehicles for personal transportation for more than 100 years already. Currently, demand for private vehicles are increasing due to the rapidly rising rates of the world population. Among the main problems related to critical increased use of private vehicles is emission, whereby this has been a significant contributor to global warming, which has become an acute issue that must be faced by everyone. As a result, the government and related agencies have come up with more stringent standards to curb the problem of emissions and fuel efficiency. To obtain a wide-range full-performance high-efficiency vehicle while eliminating pollutant emissions, the most workable solution at present is the electric vehicle (EV), which driven by battery-based electric motor [6]-[10].

Generally, there are multiples important steps and attention requirements to make a selection of electric motor for EV propulsion systems, and the automotive industry is still hunting for the most appropriate one. In this case, the key features are efficiency, reliability, and cost. The process of selecting the appropriate electric propulsion systems should be carried out at the system level. Mainly, the choice of electric-propulsion systems for EV depends on three factors; driver's expectation, vehicle design constraints, and energy source. With these considerations, the specific motor operating points are difficult to define [11]. Hence, selecting the most appropriate electric-propulsion system for the EV is always a challenging task. At present, the major type of electric motors for EVs is the Flux Switching Machine (FSM) which has recently become a accessible and attractive design of machine type due to its numerous advantages such as high torque density and efficiency [12-16].

In 1955, FSM was first introduced as a single-phase alternator by Rauch and Johnson, consisting an only permanent magnet as the single magnetic flux source [17]. FSM has been receiving significant attention afterward, especially in electric propulsion system application and meanwhile, the first three-phase system was later developed in 1997 by E. Hoang et al [18]. Firstly, the invented permanent magnet flux switching machine (PMFSM), which is a permanent magnet (PM) single-phase limited angle actuator, or more well known as Laws relay, with four stator slots and four rotor poles was developed. It is extended into a single-phase generator with four stator slots and four or six rotor poles. FSM comprises all flux sources in the stator. Besides the advantage of brushless machine type, FSM also has a single piece of iron rotor structure that is robust and applicable for high-speed applications [19]. Over the past ten years, many new FSM topologies have been developed for various applications, ranging from low-cost domestic appliances, automotive, wind power, aerospace, and others [20].

In general, FSM can be broken down into three major clusters namely permanent magnet flux switching motor [PMFSM], field excitation flux switching motor [FEFSM], and hybrid excitation flux switching motor [HEFSM]. Both PMFSM and FEFSM have only one single main excitation flux source, respectively induced by permanent magnet and field excitation coil [FEC], whereas both PM and FECs are being used to generate flux in HEFSM. On the other hand, the armature winding and permanent magnet are both stationary in PMFSM but magnetic flux linkage can be altered either positive or negative polarity depends on the position of the rotating part. The concept of FSM is actually involved changing the polarity of the flux linking the armature winding by the motion of the rotor [21]. Finally, the excitation flux produced by permanent magnet flows from stator to rotor and oppositely from the rotor to the stator to accomplish one complete cycle. Similarly, this particular operation and principle take place for the rest of FEFSM and HEFSM as well.

However, in FEFSM the excitation source used is FE, which has lower flux strengthening as compared to PMs and hence, causes the less production of torque density. Besides, due to the usage of FEC the copper losses and copper cost is increased. On the other hand HEFSM combines the both sources to produce the torque however, due the flux cancellation effects HEFSM has complexities to produce torque.

Therefore, this research mainly focuses on the PMFSM implementing inner rotor structure along with various directions of PMs.

1.2 Problem Statements

Figure 1.1 shows a conventional 12S-10P three-phase PMFSM in which stator core consists of modular U-shaped laminated segments arranged next to each other with PMs slotted in between them. For flux switching operation principles, the PM magnetization polarity is being reversed from one magnet to another [22-24]. Stator armature winding consists of concentrated coils and each coil being wound around the stator tooth formed by two adjacent laminated segments and a magnet and it is however, inherits the disadvantage of high PM volume. Hence, variety of PMFSM designs have been reported since then. To reduce the consumption of PM, the stator

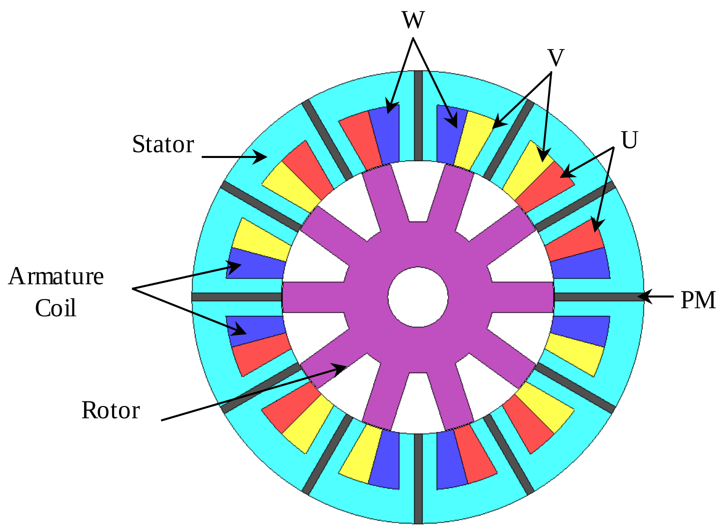

Figure 1.1: 12S-10P Conventional PMFSM Topologies

poles are replaced alternately by a simple stator tooth and therefore the new E-core is developed [24]. The stator core is merged to form an E-Core PMFSM stator and half of the PM volume in [18] is removed. The E-Core configuration is also presented in [25-27] with a combination arrangement between horizontal, and vertical of low-coercive force (LCF) magnets. The horizontal magnets are alternately attached to the stator teeth tips, and the vertical magnets remain identical as the conventional design. Moreover, the middle E-stator teeth can be removed to enlarge the slot area, and consequently, the new C-core PMFSM is introduced [28-29]. On top of these topologies, the main constraints are magnetic flux leakage at the outermost tips PM which limits the distribution of flux and also their separated stator from one segment to another that is hard to manufacture and assemble.

Therefore, to address all the shortcomings in existing PMFSMs including high PM volume, flux leakage, limited distribution of flux and manufacturing issues, new configurations of PMFSM implementing inner rotor structures are proposed in this research, such as 6S-10P salient rotor (SalR), 6S-8P spin rotor (SpR), 6S-8P segmental rotor (SegR) AlCiRaF, and 6S-10P SalR AlCiRaF are presented to execute comprehensive investigations over multiple design possibilities.

1.3 Objectives of the Study

The main objective of this research is to propose a new structure of a 3-phase permanent magnet flux switching machine using inner rotor configuration for light electric vehicles. In achieving the main objective, there are some specific objectives that must be fulfilled:

(i) To design and investigate the new structure model of three-phase PMFSM implementing inner rotor configurations for high torque density.

(ii) To analyse the performance of the proposed machines under various armature current densities for flux linkage, back-emf, cogging torque, torque speed characteristics, iron losses, copper losses of windings and efficiency.

(iii) To optimize the proposed inner rotor PMFSM and compare the simulation results with conventional PMFSM for optimum performance.

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APPENDIX A

LIST OF PUBLICATIONS

Journals:

(i) M. Jenal**,** E. Sulaiman, R. Kumar, "A New Switched Flux Machine Employing Alternate Circumferential and Radial Flux (AlCiRaF) Permanent Magnet for Light Weight EV", *Journal of Magnetics*, Vol. 21, No. 4, December 2016, pp 8846-8852 (Impact Factor of 2015 : 0.421, ISSN (Online) 2233-6656)

(ii) M. Jenal, E. Sulaiman, F. Khan and M. Z. Ahmad, "2D-FEA Based Design Study of Salient Rotor Three-Phase Permanent Magnet Flux Switching Machine with Concentrated Winding", *Applied Mechanics and Materials* Vol. 785, March 2015, pp 274-279. (Scopus Indexed)

(iii) M. Jenal and E. Sulaiman, "Investigative Study Of A Novel Permanent Magnet Flux Switching Machine Employing Alternate Circumferential And Radial Permanent Magnet" *ARPN Journal of Engineering and Applied Sciences*, Vol. 10, No. 15, August 2015, pp 6513-6519. (Scopus Indexed, ISSN 1819-6608)

(iv) M. Jenal and E. Sulaiman , "Comparative Study on a New Permanent Magnet Flux Switching Machine Configuration over Segmental and Salient Rotor Structure", *ARPN Journal of Engeering and Applied Sciences*, Vol. 10, No. 19, October 2015, pp 8846-8852 (Scopus Indexed, ISSN 1819-6608)

(v) M. Jenal**,** E. Sulaiman, H. A. Soomro, S. M. N. S. Othman, "Primary Study of a New Permanent Magnet Flux Switching Machine over Straight and Spanned Rotor Configurations", *World Journal of Engineering*, 2016. (Sopus Indexed, ISSN: 1708-5284)

Proceedings:

(i) M. Jenal, E. Sulaiman and M. Z. Ahmad, "2D-FEA Based Design Study of Salient Rotor Three-Phase Permanent Magnet Flux Switching Machine with Concentrated Winding", 9th International Power Engineering and Optimization Conference (PEOCO) 2015, 18-19 March 2015.

(ii) M. Jenal, E. Sulaiman and M. Z. Ahmad," Fundamental Study of a Novel Permanent Magnet Flux Switching Machine over Dissimilar Rotor Structures", IEEE International Magnetics Conference (INTERMAG) 2015, Beijing, China, 11-15 May 2015.

(iii) M. Jenal and E. Sulaiman, "Investigative Study of a Novel Permanent Magnet Flux Switching Machine Employing Alternate Circumferential and Radial Permanent Magnet", Renewable Energy and Green Technology International Conference (REEGETECH) 2015, Bali, Indonesia, 2 – 4 June 2015.

(iv) M. Jenal and E. Sulaiman, "Comparative Study on a New Permanent Magnet Flux Switching Machine Configuration over Segmental and Salient Rotor Structure", International Conference on Electrical and Electronic Engineering (IC3E), 2015, 10-11 August 2015.

(v) M. Jenal and E. Sulaiman, "No-Load Study of Permanent Magnet Flux Switching Machine with Various Slot Structrues of Field Excitaiton Coil", International Conference on Power, Energy and Communication Systems (IPECS) 2015, 24-25 August 2015.

(vi) M. Jenal, E. Sulaiman, F. Khan and H. A. Soomro, "Comparative Study between New Structure of PMFSM and FEFSM for Light EVs", 2015 IEEE Conference on Energy Conversion (CENCON 2015), 19-20 October 2015.

(vii) M. Jenal, E. Sulaiman, H. A. Soomro, S. M. N. S. Othman, "Primary Study of a New Permanent Magnet Flux Switching Machine over Straight and Spanned Rotor Configurations ', International Conference on Advanced Mechanics, Power and Energy 2015 (AMPE2015), 5 December 2015.

(viii) M. Jenal, E. Sulaiman, M. F. Omar, G. M. Romalan, H. A. Soomro, “Development of a Novel Permanent Magnet Flux Switching Machine Prototype for Light Weight Electric Vehicles’, IEEE Student Conference On Research And Development (SCORED2015), 13-14 December 2015.

(ix) M. Jenal, E. Sulaiman, M. Z. Ahmad, F. Khan and M. F. Omar,” A New Alternate Circumferential and Radial Flux (AlCiRaF) Permanent Magnet Flux Switching Machine for Light Weight EV”, XXIIth International Conference on Electric Machines (ICEM’2016), Lausanne, Switzerland, 4-7 Sept. 2016.

(x) M. Jenal, E. Sulaiman and R. Kumar, “Effects of Rotor Pole Number in Outer Rotor Permanent Magnet Flux Switching Machine for Light Weight Electric Vehicle”, 4th IET International Conference on Clean Energy and Technology Conference 2016 (CEAT), 14-15 November 2016.

(xi) M. Jenal, E. Sulaiman, M. Z. Ahmad, M. F. Omar, S.M.N.S. Othman, N.F. F.S. Bahrim, “Design Optimization and Electromagnetic Analysis of 6Slots-10Poles Switched Flux Machine Occupying Radial and Circumferential PM for Light Weight EV”, IEEE International Magnetics Conference (INTERMAG Europe) 2017, Dublin, R.O Ireland, 24-28 April 2017.

APPENDIX B

LIST OF AWARDS

(i) ‘12Slot-14Pole HEFSM with Iron Flux Bridge for Hybrid Electric Vehicle”, Research & Innovation Festival 2014, UTHM, 2-3 Nov.2014.

(ii) “A New Design of 3-ϕ Permanent Magnet Flux Switching Machine for Light Weight EV”, Postgraduate Poster Competition, FKEE Mind Transformation Day 2015, UTHM, 21 Sept. 2015.

(iii) “3-ϕ AlCiRaF Permanent Magnet Flux Switching Machine for Light EV”, Postgraduate Showcase Competition, Conference On Energy Conversion (CENCON2015), UTM, 19-20 Oct. 2015. (*5-Finalist*).

(iv) “AlCiRaF PMFSM”, Research & Innovation Festival 2015, UTHM, 16-17 Nov.2015 (*Bronze Medal*).

(v) “D^2 Motor for Eclimo Electric Scooter”, Malaysia Technology Expo 2016 (MTE2016), PWTC Kuala Lumpur, 18-20 Feb. 2016. (*Silver Medal*).

(vi) “30kW/80,000 RPM Electrical Generator”, Research & Innovation Festival 2016, UTHM, 14-15 Nov.2016. (*Bronze Medal*).

(vii) “Effects of Rotor Pole Number in Outer Rotor Permanent Magnet Flux Switching Machine for Light Weight Electric Vehicle”, 4th IET International Conference on Clean Energy and Technology Conference 2016 (CEAT), 14-15 November 2016 *(Best Presenter).*

(viii) “Mobile Power Supply (MoPS),” International Innovation and Design Johor (IIDJ 2017), Johor Bahru, 9 March 2017 (*Gold Medal*).

VITA

The author was born in Johor, Malaysia, on December 04, 1977. During his secondary school, he went to Sekolah Menengah Muzaffar Syah, Melaka and completed his B.E Degree in Electrical Engineering from University Teknologi Malaysia in year 2000. Upon graduation in he has been working under Sharp Manufacturing Malaysia as an Engineer. He received his M.E Degree in Electrical Engineering from University Tun Hussein Onn Malaysia in 2009 and therefore serve as a lecturer in the same university. Currently, he is pursuing his Ph.D. Degree at Department of Electrical Power Engineering, University Tun Hussein Onn Malaysia. His research interests include design and optimization of Permanent Magnet Flux Switching Machines (PMFSMs) specializing in non-overlap windings configuration.