DESIGN OPTIMIZATION OF SINGLE-PHASE INNER-ROTOR AND OUTER-ROTOR HYBRID EXCITATION FLUX SWITCHING MACHINE FOR EV APPLICATIONS

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A thesis submitted in fulfillment of the requirement for the award of the Master of Electrical Engineering

Faculty of Electric and Electronic Engineering Universiti Tun Hussein Onn Malaysia

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For my beloved mother and father,
Che Zarah Binti Mohd Zain and Mazlan bin Mamat,
my siblings,
Muizzuddin Azfar Mazlan and Murtaza Asmuin Mazlan
my friends,
and my lovely family
Thank you for your prayers, support, guidance and love
ACKNOWLEDGEMENT

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Last but not least, appreciation goes to everyone who has contributed directly or indirectly towards the compilation of this thesis and may your charity and goodwill will be blessed.
ABSTRACT

Electric Vehicle (EV) is considered as an ultimate eco-friendly car and this is highly expected to be popularized in the future. One of the main candidates of electric machine for an EV drive is a flux switching machine (FSM). However, since the designed machine consists of three-phase complicated winding, the copper loss which contributes to efficiency of the machine is expected to be increased. Furthermore, the three-phase armature winding has a large area size of the total system. Due to the complicated three-phase armature winding that contribute to high copper losses, a single-phase inner-rotor and outer-rotor Hybrid Excitation Flux Switching Machine (HEFSM) with much simpler structure and less armature coil consumption are introduced in this research. Various characteristics of HEFSM are investigated by analytical approaching based in finite element analysis using JMAG software. The project implementation of this research is divided into three parts including design, analyze and optimize. Firstly, the impact of a rotor pole number of the proposed is investigated for inner-rotor and outer-rotor configuration in order to determine the optimal performances of the rotor poles combinations. Then 8S-4P and 8S-8P HEFSM are chosen for optimization analysis. The combination of 8S-8P inner-rotor HEFSM have best performance with 284Nm maximum torque, 62.98kW maximum power and 90% efficiency. Then 8S-8P HEFSM have been compared with three-phase 12S-14P HEFSM in term of copper loss, weight and efficiency. As conclusion, the final design machine produce 12.45% less copper loss, 8.88% less weight and with almost similar efficiency compared to three-phase configuration.
# CONTENTS

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE</td>
<td>i</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td>CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF PUBLICATIONS</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF AWARDS</td>
<td>xviii</td>
</tr>
</tbody>
</table>

## CHAPTER 1 INTRODUCTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Objectives</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Scope</td>
<td>5</td>
</tr>
<tr>
<td>1.5 Outlines of Thesis</td>
<td>6</td>
</tr>
</tbody>
</table>

## CHAPTER 2 LITERATURE REVIEW

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Introduction to Flux Switching Machine</td>
<td>8</td>
</tr>
</tbody>
</table>
CHAPTER 3 METHODOLOGY

3.1 Project Methodology 20
3.2 Part 1: Design 21
3.3 Part 2: Analysis 25
3.4 Part 3: Optimize 26
3.5 Summary 29

CHAPTER 4 RESULTS

4.1 Various Rotor Pole Analysis 30
4.1.1 Inner-rotor and Outer-rotor HEFSM Various Rotor Pole Analysis 30
4.1.2 No Load Analysis 32
4.1.2.1 Flux Linkage at Maximum DC FEC Current Density, J_E 32
4.1.2.2 Induced Voltage at Open Circuit Condition 33
4.1.2.3 Cogging Torque 34
4.1.3 Load Analysis 35
4.1.3.1 Torque and Power vs. J_E at Maximum Armature Coil Current Density, J_A 35
4.1.4 Summary of Rotor Poles Study

4.2 Design Optimization Single-Phase Inner-Rotor and Outer-Rotor 8S-4P and 8S-8P HEFSM

4.2.1 No Load Analysis
  4.2.1.1 Flux Linkage at PM and Maximum DC FEC Current Density, $J_E$
  4.2.1.2 Cogging Torque
  4.2.1.3 Induced Voltage/Back EMF of PM with DC FEC

4.2.2 Load Analysis
  4.2.2.1 Torque versus FEC Current Density, $J_E$ at Maximum Armature Coil Current Density, $J_A$
  4.2.2.2 Instantaneous Torque Characteristic of Maximum $J_E$ and $J_A$
  4.2.2.3 Rotor Mechanical Strength
  4.2.2.4 Torque and Power Vs. Speed Characteristic
  4.2.2.5 Motor Losses and Efficiencies

4.2.3 Summary of Optimization

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Introduction

5.2 Conclusion

5.3 Future Work

REFERENCES
### LIST OF TABLES

1.1 Design Restrictions and Specifications of HEFSM

3.1 Material for Rotor, Stator, Armature Coil, Permanent Magnet and FEC

4.1 Parameter of Inner-Rotor and Outer-Rotor HEFSM

4.2 Summary of Rotor Pole Study for Inner-Rotor HEFSM

4.3 Summary of Rotor Pole Study for Outer-Rotor HEFSM

4.4 Design Parameters of Initial and Final 8S-4P Inner-Rotor and Outer-Rotor HEFSM

4.5 Design Parameters of Initial and Final 8S-8P Inner-Rotor and Outer-Rotor HEFSM

4.6 Input Current of FEC of Initial and Final 8S-4P Inner-Rotor and Outer-Rotor HEFSM

4.7 Input Current of FEC of Initial and Final 8S-4P Inner-Rotor and Outer-Rotor HEFSM

4.8 Summary of Instantaneous Torque for Final Design HEFSMs

4.9 Weight, Power and Torque Density of Final Design HEFSM

4.10 Loss and Efficiency of Inner0Rotor and Outer-Rotor 8S-4P HEFSM

4.11 Loss and Efficiency of Inner0Rotor and Outer-Rotor 8S-8P HEFSM

4.12 Overall Performances of The Design of Single-Phase 8S-4P and 8S-8P Inner-Rotor and Outer-Rotor HEFSM

4.13 Comparison Single-Phase 8S-8P and Three-Phase 12S-14P Inner-Rotor and Outer-Rotor Configuration
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Four Main Candidates of Electric Machine for HEV Drives</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Classification of Flux Switching Machine (FSM)</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Operating Principle of Permanent Magnet Flux Switching Machine (PMFSM)</td>
<td>9</td>
</tr>
<tr>
<td>2.3</td>
<td>Operating Principle of Field Excitation Flux Switching Machine (FEFSM)</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>Operating Principle of Hybrid Excitation Flux Switching Machine (HEFSM)</td>
<td>12</td>
</tr>
<tr>
<td>2.5</td>
<td>Operating Principle of Outer-rotor HEFSM</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>Example of Three-Phase FSM</td>
<td>16</td>
</tr>
<tr>
<td>2.7</td>
<td>Example of Single-Phase FSM</td>
<td>18</td>
</tr>
<tr>
<td>3.1</td>
<td>Project Implementation</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Design and Condition Setting Proposed Inner-Rotor and Outer-Rotor HEFSM</td>
<td>21</td>
</tr>
<tr>
<td>3.3</td>
<td>Initial Design of HEFSM</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Direction of Permanent Magnet</td>
<td>23</td>
</tr>
<tr>
<td>3.5</td>
<td>Direction of FEC</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>The Direction of Armature Coil</td>
<td>25</td>
</tr>
<tr>
<td>3.7</td>
<td>Analysis Procedure</td>
<td>26</td>
</tr>
<tr>
<td>3.8</td>
<td>Optimization Procedure</td>
<td>27</td>
</tr>
<tr>
<td>3.9</td>
<td>Design Parameter of Inner-Rotor and Outer-Rotor HEFSM</td>
<td>27</td>
</tr>
<tr>
<td>4.1</td>
<td>Initial Design of the IR-HEFSM Configurations</td>
<td>31</td>
</tr>
<tr>
<td>4.2</td>
<td>Initial Design of the OR-HEFSM Configurations</td>
<td>31</td>
</tr>
<tr>
<td>4.3</td>
<td>Magnetic Flux Linkage at Various Rotor Pole Numbers</td>
<td>33</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
<td></td>
</tr>
<tr>
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<tr>
<td>A</td>
<td>Ampere</td>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>Dy</td>
<td>Dysprosium DC</td>
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<tr>
<td>DC</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<td></td>
</tr>
<tr>
<td>FEC</td>
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</tr>
<tr>
<td>FEFSM</td>
<td>Field Excitation Flux Switching Motor</td>
<td></td>
</tr>
<tr>
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<td>Hybrid Excitation Flux Switching Motor</td>
<td></td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
<td></td>
</tr>
<tr>
<td>IMs</td>
<td>Induction Motors</td>
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<tr>
<td>IPMSMs</td>
<td>Interior Permanent Magnet Synchronous Motors</td>
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</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<tr>
<td>J_E</td>
<td>FEC current density</td>
<td></td>
</tr>
<tr>
<td>J_A</td>
<td>Armature coil current density</td>
<td></td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
<td></td>
</tr>
<tr>
<td>Mm</td>
<td>Millimeter</td>
<td></td>
</tr>
<tr>
<td>Nm</td>
<td>Newton meter</td>
<td></td>
</tr>
<tr>
<td>Nd</td>
<td>Neodymium</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
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<td>PMFSM</td>
<td>Permanent Magnet Flux Switching Motor</td>
<td></td>
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<tr>
<td>r/min</td>
<td>Revolution per minute</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Volt</td>
<td></td>
</tr>
<tr>
<td>Wb</td>
<td>Weber</td>
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</tr>
</tbody>
</table>
LIST OF PUBLICATIONS

Journals:


Proceedings:


(iii) Mohamed Mubin Aizat Mazlan, Erwan Sulaiman, Zhafir Aizat Husin, Syed


CHAPTER 1

INTRODUCTION

1.1 Introduction

With the increasing number of world population, the demand for vehicles for personal transportation has increased dramatically in the past decades. This leads to serious problems called ‘global warming’. One of the main causes of global warming is Internal Combustion Engine (ICE). From the report in year 2013 [1], about 26% of global carbon dioxide (CO₂) emission in year 2013 came from the vehicles. By the year 2020, it is expected that CO₂ emission rate from vehicles will increase two times with economic growth.

Hybrid Electric Vehicle (HEV) is considered as an ultimate eco-friendly car and this is highly expected to be popularized in the future [2]-[4]. The important of the basic characteristic requirements of an electric motor for HEV drive systems are high torque at low speed, high power density, and constant power at high speed as well as high efficiency [5].

Electric vehicles (EVs) seem like an ideal solution to deal with the energy crisis and global warming since they have zero oil consumption and zero emissions. EVs have several advantages over HEV such as EVs emit no tailpipe pollutants, although the power plant producing the electricity may emit them and EV provide quiet, smooth operation and stronger acceleration and require less maintenance than HEV. Therefore, EV is now regarded as an ultimate eco-friendly car and is widely expected to become more popular in the very near future [6]-[8].

Various electric motors used in HEV and EV have been designed and successfully installed in the vehicles such as Honda Jazz, Toyota Prius, Mitsubishi Mirage and Nissan Leaf as illustrated in Figure 1.1. Figure 1.1(a) illustrates an
example of Permanent Magnet Synchronous Machine (PMSMs) installed in Lexus, Prius and Nissan Leaf. Although PMSM has the advantage of high torque density and high efficiency, still it has the problem of PM demagnetization, mechanical damage of rotor’s magnet and uncontrolled flux of PM [9]-[11].

Figure 1.1: Four Main Candidates of Electric Machine for HEV Drives
(a) Permanent Magnet Synchronous Machines (b) DC motor (c) Induction Motor (d) Switched Reluctant Motor
Furthermore, Figure 1.1(b) depicts an example of Direct Current (DC) motor used in HEV and EV. Since DC motor utilizes DC supply battery, the control principle becomes simpler that makes it widely accepted in electric propulsion system. However, DC motor drives have major disadvantages such as low reliability and high maintenance [12]. Thus DC motors are unsuitable for maintenance-free drives.

At present, induction motor (IM) as shown in Figure 1.1(c), are generally established as the most potential candidate for the electric propulsion of EV and HEVs, due to their reliability, ruggedness, low maintenance, and low cost [13]-[14]. However, IM drives have demerits such as high loss, low efficiency and low power factor [15]-[17].

Figure 1.1(d) shows the structure of a switched reluctant motor (SRM) which is invented to overcome the permanent magnet motor problem. SRM has no PM and robust rotor structure but it is not suitable for HEV and EV due to large torque ripples and noisy [18]-[19]. Although the SRMs have been successfully installed in HEV and EV, the drawbacks of each electric motor can further be improved and optimized.

In order to overcome the previous motor problems, hybrid excitation flux switching machine (HEFSM) in which all flux source are located in stator body is introduced in this research. Proposed HEFSM that consists of permanent magnet (PM) and field excitation coil (FEC) as main flux sources is more advantageous compared to existing electric motor [20]-[21]. HEFSM with a robust rotor structure similar with SRM is suitable for extreme driving condition. Additionally, an extra advantage of locating PM and FEC at the stator core provide a simple cooling system for this machines. In addition, the FEC can control constant PM flux to produce variable flux capabilities, which can enhance more torque and power.

1.2 Problem Statement

Several invention of HEFSM for EV application has been proposed. Three-phase HEFSM have been developed for various EV drives applications with strong performance in term of high torque, high power and high speed ability. This is
proven by three-phase inner-rotor HEFSM [2] and outer-rotor HEFSM [21]. However, the proposed machines have problems of high torque ripple and high induced voltage [22]-[24]. Moreover, since the designed machine consists of three-phase complicated winding, the copper loss which contributes to efficiency of the machine is expected to be increased. Furthermore, the three-phase winding has high voltage supply and use big battery size and complex inverter. Therefore the three-phase armature winding has a large area of the total system [25]. Due to complicated three-phase armature winding that contribute to high copper losses, a single-phase inner-rotor and outer-rotor HEFSM with much simpler structure and less armature coil consumption are introduced in this research. It is obvious that both inner rotor and outer-rotor configurations can be applied for normal and direct drive HEV and EV system respectively. Moreover, single-phase also requires low voltage supply, uses small battery size and simple inverter. Therefore the single-phase armature winding has a small area of the total system.

The performances of the proposed machine under some restrictions and specifications will be analyzed and evaluated. The proposed machine is expected to provide high efficiency, high durability and less copper losses compared to the three-phase winding of HEFSM.

1.3 Objectives of Project

The objectives of this research are:

(i) To design a single-phase inner-rotor and outer-rotor hybrid excitation flux switching motor for electric vehicle applications.

(ii) To analyze a single-phase inner-rotor and outer-rotor hybrid excitation flux switching motor for electric vehicle applications.

(iii) To optimize the performances of the 8S-4P and 8S-8P single-phase inner-rotor and outer-rotor hybrid excitation flux switching motor for electric vehicle applications.
1.4 Scopes of Project

The scopes of this research are divided into three parts based on the objectives. The scopes are:

(i) The design restrictions, target specifications and parameters of the proposed HEFSM for EV applications are listed in Table 1.1 [26]. The electrical restrictions related with the inverter such as maximum 240V DC bus voltage and maximum 360A inverter current are set. Assuming water jacket system is employed as the cooling system for the machine, the limit of the current density is set to the maximum 30A_{rms}/mm² for armature winding and 30A/mm² for FEC, respectively. The outer diameter, the motor stack length, the shaft radius and the air gap of the main part of the machine design being 264mm, 70mm, 30mm and 0.8mm respectively. The target of maximum torque and power for proposed single-phase are 111Nm and 41kW respectively which are one third of three-phase HEFSM.

(ii) The performances of rotor poles study are investigated in order to determine the optimal performances. The no load and load analysis such as flux linkage, cogging torque, induced voltage and torque and power vs. \( J_E \) are determined.

Table 1.1: Design Restrictions and Specifications of HEFSM [26]

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Three-Phase HEFSM</th>
<th>Single-Phase HEFSSM</th>
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</thead>
<tbody>
<tr>
<td>Max. DC-bus voltage inverter</td>
<td>V</td>
<td>650</td>
<td>240</td>
</tr>
<tr>
<td>Max. inverter current</td>
<td>( A_{\text{rms}} )</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Max. current density in armature winding, ( J_a )</td>
<td>( A_{\text{rms}}/\text{mm}^2 )</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Max. current density in excitation winding, ( J_e )</td>
<td>( A/\text{mm}^2 )</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>mm</td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td>Motor stack length</td>
<td>mm</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Shaft radius</td>
<td>mm</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Air gap length</td>
<td>mm</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>PM weight</td>
<td>kg</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>Nm</td>
<td>&gt;333</td>
<td>&gt;111</td>
</tr>
<tr>
<td>Maximum power</td>
<td>kW</td>
<td>&gt;123</td>
<td>&gt;41</td>
</tr>
</tbody>
</table>
(iii) The motor 8S-4P and 8S-8P single-phase inner-rotor and outer-rotor configuration are chosen from rotor pole analysis and are optimized by using deterministic optimization method [27] and treated to all parameters until the optimum performances are achieved. Then the outer-rotor motor is compared to inner-rotor 8S-4P and 8S-8P HEFSM with the same design restrictions and specifications. Finally, loss analysis, structural analysis and efficiency are analyzed and compared for 8S-4P and 8S-8P inner-rotor and outer-rotor configuration HEFSM.

1.5 Outlines of Thesis

This thesis deals with the design studies on single-phase inner-rotor and outer-rotor hybrid excitation flux switching machine (HEFSM) for EV applications. The thesis is divided into 5 chapters and the summary of each chapter are listed as follows:

(i) Chapter 1: Introduction
The first chapter gives some introduction about the research including research background, related works on EV and some explanation regarding inner-rotor and outer-rotor configuration used in EV. Then problems of current three-phase winding used in EV are highlighted and the research objectives are set to solve the problems.

(ii) Chapter 2: Literature Review
The second chapter explains some introduction and classifications of FSM including the example of PMFSM, HEFSM and FEFSM, the operating principle and the proposed HEFSM for HEV applications. Then the review of single-phase for all FSM is explained.

(iii) Chapter 3: Methodology
The third chapter describes the project implementation of this research. The project implementation is divided into three parts including design, analysis and optimization. The design is divided into two parts that are geometry editor and JMAG-Designer. Then the design is analyzed at no load and load analysis such as flux linkage, cogging torque, induced voltage and torque and power vs. maximum $J_E$. Finally the “deterministic optimization method” is
used and treated to all parameters until the optimum performances are achieved.

(iv) Chapter 4: Result
In this chapter, various combinations of slot-pole inner-rotor and outer-rotor HEFSMs such as 8S-4P, 8S-8P, 8S-12P, 8S-16P and 8S-20P are designed and analyzed. Among various slot-pole combinations of HEFSM, the combination of 8S-4P and 8S-8P of inner-rotor and outer-rotor configuration has better performance and chosen for design optimization. The design is optimized by using deterministic optimization method and treated to all parameters until the optimum performances are achieved. The results of the initial and final design which met the target performances such as maximum flux linkage, cogging torque, induced voltage, instantaneous torque characteristic, rotor mechanical stress and motor losses and efficiency are analyzed and discussed.

(v) Chapter 5: Conclusion
The final chapter describes and concludes the summary of the research and pointed out some future works for design improvements.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Flux Switching Motor

Generally, the flux switching motor (FSM) can be categorized into three groups that are permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSM combines both PM and FEC as their main flux sources. Figure 2.1 illustrates the general classification of FSM.

![Figure 2.1: Classification of Flux Switching Machine (FSM)](image)

FSM consists of the rotor and stator. The rotor consist of only single structure which is iron core thus allowing its simple construction and inherent robustness to be retained while both field and armature windings are on the stator. The operation of the motor is based on the principle of switching flux. The term “flux switching” is coined to describe machines in which the stator tooth flux switches polarity
following the motion of a salient pole rotor [28-29]. All excitation sources are on the stator with the armature and field allocated to alternate stator teeth.

Flux is produced in the stator of the machine by permanent magnet or by dc current flowing in the field winding. The orientation of the field flux is then simply switched from one set of stator poles to another of stator poles by reversing the polarity of the current in the armature winding.

### 2.1.1 Permanent Magnet Flux Switching Motor

Permanent magnet flux switching motor (PMFSM) is a simple construction. The stator consists of PM and armature windings and due to this it provides some advantages such easy cooling and better suitability for high speed applications [30]. PMFSM is popular due to high power density, efficiency and it uses PM to generate flux. Unfortunately, the generated flux produced is fixed and will not change-diverged which means it is constant flux because of characteristics of the PM.

![Diagram of PMFSM showing flux linkage](image)

**Figure 2.2:** Operating Principle of PMFSM (a) Flux Linkage Correspond to One Polarity (b) Flux Linkage Switch Polarity as the Salient Pole Rotates [31]-[33]

Figure 2.2 demonstrates the general ideal of the operating principle of the PMFSM where the red arrows indicate the flux line of PM as an instance. The flux-
linkage corresponds to one polarity is when the relative position of the rotor poles and a particular stator tooth are as in Figure 2.2 (a). But in Figure 2.2 (b) the polarity of the flux-linkage reverses as the relative position of the rotor poles and the stator tooth changes. The salient pole rotor rotates when the flux linkage switches polarity [31]-[33].

2.1.2 Field Excitation Flux Switching Motor

In spite of the fact that permanent magnet (PM) machines exhibit high torque density and high efficiency, the rare earth magnet material, is expensive and the working environmental temperature may limit its application [34]-[36].

![Diagram](image)

Figure 2.3: Operating Principle of FEFSM (a) $\theta_e=0^\circ$ and (b) $\theta_e=180^\circ$ Flux Moves from Stator to Rotor (c) $\theta_e=0^\circ$ and (d) $\theta_e=180^\circ$ Flux Moves from Rotor to Stator [37]-[39]
A Flux-switching machine with field excitation coil is recommended in order to reduce the cost. The conventional DC winding excited synchronous machine employs the field winding on the rotor and the slip-rings are required to supply the field current [33].

Figure 2.3 (a) reveals the operating principle of the FEFSM and Figure 2.3 (b) reveals the direction of the FEC fluxes into the rotor. Figure 2.3 (c) and (d) indicate the direction of FEC fluxes into the stator which produces a complete one cycle flux. Alike with PMFSM, the flux linkage of FEC switches its polarity by following the movement of salient pole rotor which creates the term “flux switching”. Each reversal of armature current shown by the transition between Figure 2.3(a) and (b), causes the stator flux to switch between the alternate stator teeth. The flux does not rotate but shifts clockwise and counter clockwise with each armature-current reversal [37]-[39].

2.1.3 Hybrid Excitation Flux Switching Motor

Hybrid Excitation Flux Switching Motor (HEFSM) is the combination of PM and FE. HEFSM has significantly less magnet and higher torque density than those of a conventional PMFSM.

By applying negative d-axis current, the PM flux can be counteracted but with the disadvantage of increase in copper loss and thereby reducing the efficiency, reduced power capability, and also possible irreversible demagnetization of the PMs. Thus, HEFSM is an alternative option where the advantages of both PM machines and DC FEC synchronous machines are combined. As such HEFSMs have the potential to improve flux weakening performance, power and torque density, variable flux capability, and efficiency which have been researched extensively over many years [40].

The operating principle of the proposed HEFSM is illustrated in Figure 2.4, where the red and blue line indicate the flux from PM and FEC, respectively. In Figure 2.4(a) and (b), since the direction of both PM and FEC fluxes are in the same polarity, both fluxes are combined and move together into the rotor, hence producing more fluxes with a so called hybrid excitation flux. Furthermore, in Figure 2.4(c) and
(d), where the FEC is in reverse polarity, only flux of PM flows into the rotor while the flux of FEC moves around the stator outer yoke which results in less flux excitation [41]-[42].

![Diagram showing operating principle of HEFSM](image)

Figure 2.4: Operating Principle of HEFSM (a) $\theta_e=0^\circ$-More Excitation (b) $\theta_e=180^\circ$-More Excitation (c) $\theta_e=0^\circ$-Less Excitation (d) $\theta_e=180^\circ$-Less Excitation [41]-[42]

### 2.2 Outer-Rotor vs. Inner-Rotor Configurations

Most of commercial EV used single motor and transmission gears coupled to the wheels. This system leads to the transmission losses and reduce the efficiency and
reliability of the motor [43]-[44]. Therefore, in-wheel direct drive mechanism is introduced to overcome this problem. In-wheel direct drive eliminates the mechanical transmission, differential gears and drive belts.

![Operating Principle of Outer-rotor HEFSM](image)

Figure 2.5: Operating Principle of Outer-rotor HEFSM (a) $\theta_e = 0^\circ$ (b) $\theta_e = 180^\circ$

More Excitation, (c) $\theta_e = 0^\circ$ (b) $\theta_e = 180^\circ$ Less Excitation [56]-[57]

Since the in-wheel direct drive with outer-rotor configuration is more practical for direct drive application, several invention of in-wheel mechanism for EV application has been proposed. For example 12S-22P outer-rotor permanent-magnet flux-switching machine (PMFSM) for electric propulsion in a lightweight electric vehicle has been proposed [45]. The proposed machine is a highly possible
candidate for in-wheel direct-drives. This PMFSM has physical compactness, robust 
rotor structure, higher torque and power density and high efficiency. However 
PMFSM has several disadvantages of uncontrolled flux and demagnetization [46].

The operating principle of OR-HEFSM is illustrated in Figure 2.5. The single 
piece of rotor that makes the motor more robust similar to SRM is shown in the 
upper part, while the stator that consists of PMs, FECs, and armature coils are 
located in the lower part. The PM and FEC are placed between two stator poles to 
generate excitation fluxes that create the term of “hybrid excitation flux”. Figure 2.5 
(a) and (b) demonstrate the flux generated by PM and FEC flow from the stator into 
the rotor and from the rotor into the stator, respectively, to produce a complete one 
flux cycle. The combined flux generated by PM and FEC established more excitation 
fluxes that are required to produce higher torque of the motor. When the rotor rotate 
clockwise, the rotor pole goes to the next stator tooth, hence switching the magnitude 
and polarities of the flux linkage. The flux does not rotate but shifts clockwise and 
counter clockwise in direction with each armature current reversal. According to 
Figure 2.5 (c) and (d), only the PM flux flows from the stator into the rotor and from 
the rotor into the stator, respectively, while the FEC flux is only circulating on its 
particular winding slots. This condition establishes less excitation flux and generates 
less torque [47]-[48].

2.3 Reviews on Three-Phase Winding of Flux Switching Machine (FSM)

Early examples of three-phase Flux Switching Machine (FSM), the three-phase 
PMFSM, FEFSM and HEFSM are developed as shown in Figure 2.6 (a), (b) and (c), 
respectively. Figure 2.6(a) shows a typical three-phase 12S-10P PMFSM, where the 
salient pole stator core consists of modular U-shaped laminated segments placed next 
to each other with circumferentially magnetized PMs placed in between them. For 
the flux switching principles, the PM magnetization polarity is being reversed from 
one magnet to another [49]-[51].

The 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. The salient pole rotor is similar to that of SRMs, which is more robust and
suitable for high speed applications, and the difference in the number of rotor poles and stator teeth is two. In contrast with conventional IPMSM, the slot area is reduced when the magnets are moved from the rotor to the stator, it is easier to dissipate the heat from the stator and the temperature rise in the magnet can be controlled by proper cooling system.

In addition, since the flux path generated by mmf of the armature windings and PMs are magnetically in parallel, rather than in series as in conventional IPMSM, the influence of the armature reaction field on the working point of the PMs is almost eliminated. As a result, the specific electric loading and the specific torque capability of a PMFSM can be increased. In addition, a high per-unit winding inductance can be readily achieved. Thus, such machines are eminently suitable for constant power operation over a wide speed range, i.e., they can have a high flux-weakening capability [52].

The 12S-10P FEFSM in Figure 2.6(b) is redesigned from the 12S-10P PMFSM in Figure 2.6(a) in which the PM is removed from the stator and half of the armature coil slots in the upper layer are placed with the FEC windings as explained in [53]. The FEC are arranged with alternate DC current source polarity to produce two flux polarities, similar with PM polarity of 12S-10P PMFSM discussed in Figure 2.6(a). However, since the isolated and unused stator teeth reduce the performance of the machine, further investigations into improvements of the machine design of three phase FEFSMs should be made.

Meanwhile, the HEFSM shown in Figure 2.6(c) is a 3-phase 12S-10P PMFSM which incorporates the FEC at outer extremity of the stator [54]-[55]. However, the outer diameter of the machine is significantly enlarged for the FEC winding, which in turn reduces torque density. In addition, the PMs in the PMFSM can be partially replaced by the DC FEC windings and consequently, several HEFSM topologies were developed as in [56]-[57]. Although they have no overlapped between the armature coil and FEC, the torque capability is significantly reduced due to less PM volume.
Furthermore, it is clear that to realize the hybrid topology of Figure 2.6(c), both PM and armature coil volume should be sacrificed, when compared with the conventional 3-phase 12S-10P PMFSM of Figure 2.6(a), while keeping the machine stator outer radii as constant. From the conventional PMFSM topology, it is possible to replace some of the magnet material with DC FECs and therefore create several HEFSM topologies without loss of armature coil. This represents the simplest
method of hybridizing the conventional PMFSM topology with FEC as it retains the existing stator and rotor dimensions and structure.

Based on the overview of various three-phase FSMs that have been discussed, three-phase FSM produce high instant power, high power density, and high power at high speed for cruising. Three-phase FSM also produce fast torque response and high torque at low speed for starting and climbing.

2.4 Reviews on Single-Phase Winding of Flux Switching Machine (FSM)

Although a few three-phase FSM have been designed in recent years, the fundamental three-phase drawbacks such as high copper loss, complicated winding, high cost and high supply voltage are yet to be overcome. Thus a single-phase FSM have been fundamentally design. The advantages of single-phase FSM are simple design due to single winding, less copper loss and easy to manufacture. Single-phase FSM also less controlled circuit and simple control system compared to three-phase FSM. Figure 2.7 illustrates the single-phase of FSMs.

Figure 2.7(a) shows a typical single-phase 6S-4P PMFSM, where the salient pole stator ore consists of modular U-shaped laminated segments placed next to each other with circumferentially magnetized PMs placed in between them. For the flux switching principles, the PM magnetization polarity is being reversed from one magnet to another [58]-[59]. The 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. In the same figure, all armature coil phases have the same winding configuration and are placed in the stator core to form 6 slots of windings. The salient pole rotor is similar to that of SRMs, which is more robust and suitable for high speed applications, and the difference in the number of rotor poles and stator teeth is two. In contrast with conventional IPMSM, the slot area is reduced when the magnets are moved from the rotor to the stator, it is easier to dissipate the heat from the stator and the temperature rise in the magnet can be controlled by proper cooling system. In addition, since the flux path generated by mmf of the armature windings and PMs are magnetically in parallel, rather than in series as in conventional IPMSM, the influence of the armature reaction field on the working
point of the PMs is almost eliminated. As a result, the specific electric loading and the specific torque capability of a PMFSM can be increased. In addition, a high per-unit winding inductance can be readily achieved. Thus, such machines are eminently suitable for constant power operation over a wide speed range, i.e., they can have a high flux-weakening capability [60].

Figure 2.7: Example of Single-Phase FSM (a) Single-Phase PMFSM (b) Single-Phase FEFSM (c) Single-Phase HEFSM
The concept of the FEFSM involves changing the polarity of the flux linking with the armature winding, with respect to the rotor position. Early examples of single-phase 4S-2P FEFSM that employs with a DC FEC on the stator, a toothed-rotor structure and fully-pitched windings on the stator is shown in Figure 2.7(b) [61]. From the figure, it is clear that two armature coil and FEC windings are placed in the stator which overlapped each other. The viability of this design was demonstrated in applications requiring high power densities and a good level of durability [62]–[64]. The novelty of the invention was that the single-phase ac configuration could be realized in the armature windings by deployment of DC FEC and armature winding, to give the required flux orientation for rotation. The torque is produced by the variable mutual inductance of the windings. The single-phase FEFSM is very simple motor to manufacture, coupled with a power electronic controller and it has the potential to be extremely low cost in high volume applications. Furthermore, being an electronically commutated brushless motor, it inherently offers longer life and very flexible and precise control of torque, speed, and position at no additional cost.

Hybrid excitation flux switching machines (HEFSMs) are those which utilize primary excitation by PMs as well as DC FEC as a secondary source. HEFSM is an alternative option where the advantages of both PM machines and DC FEC synchronous machines are combined. Figure 2.7(c) shows a single-phase 6S-4P HEFSM in which the active parts are arranged in three layers in the stator. The inner stator consists of the armature windings, followed by the FECs in the middle layer, while the PMs are placed in outer stator as discussed in [65]-[66]. However, the machine has low torque density and long end winding for the DC FECs, which overlaps the armature windings, and increase copper loss.

2.6 Summary

In this chapter, the overview and classifications of various FSMs are discussed. The PMFSM, FEFSM and HEFSM have their own advantages and disadvantages which requires further investigations to extract higher performances for several applications.
CHAPTER 3

METHODOLOGY

3.1 Project Methodology

The project implementation of this research is divided into three parts based on objectives including design, analyze and optimize. The general process of research methodology is illustrated in Figure 3.1. An analytical study, Finite Element Analysis (FEA) study based on reluctant network is used to evaluate magnetic flux is needed to design the inner-rotor and outer-rotor HEFSM. Using FEA based on JMAG-Designer Software allows obtaining information that is not available through an actual device test because it gives us substantially greater insight into the device's performance. JMAG is simulation software for electromechanical design striving to be easy to use while providing versatility to support users from conceptual design to comprehensive analyses. JMAG can accurately capture and quickly evaluate complex physical phenomena inside of machine.

![Diagram](image)

Figure 3.1: Project Implementation
3.2 Part 1: Design

The project implementation is divided into two parts that are geometry editor and JMAG-Designer. The design process of single-phase inner-rotor and outer-rotor HEFSM parts is demonstrated in Figure 3.2.

In this design study, the motor are divided into two groups, namely, those related to stator iron core and rotor iron core. On the stator iron core, it is subdivided into three components which are the PM shape, FEC slot shape, and armature slot shape. The rotor parameters involved are the inner rotor radius, rotor pole depth, and rotor pole arc width. The PM slot shape parameters are the PM depth and the PM width, while for the FEC slot parameters are FEC slot depth and FEC slot width, and
respectively. Finally, the armature coil parameters are armature coil slot depth and the armature coil slot width. The initial designs are demonstrated in Figure 3.3.

![Figure 3.3: Initial Design of HEFSM](image)

(a) Inner-Rotor HEFSM (b) Outer-Rotor HEFSM

The selections of the initial design single-phase HEFSMs are based on the main geometrical dimensions identical to existing three-phase HEFSM in which the stator outer diameter, stack length and shaft are set respectively to 132mm, 70mm and 30mm as mentioned earlier in Table 1.1 with following assumptions follows:

(i) The rotor radius is 70% for inner rotor and 83% for outer rotor of the size of motor and both within the range of general machine split ratio [67]-[68].

(ii) The rotor pole depth is half of the rotor to give much depth for the flux to flow while keeping the suitable distance of the rotor inner part to avoid flux saturation and to keep the acceptable rotor mechanical strength, simultaneously.

(iii) The rotor pole width is defined as in equation (3.1) [69].

\[
\sum \text{Stator Tooth Width} = \sum \text{Rotor Tooth Width} \quad (3.1)
\]

(iv) The PM depth and width is calculated based on the volume of 1kg permanent magnet. The PM depth is approximately one third of stator depth and expecting give more space for flux to flow from stator to rotor. The direction of permanent magnet are shown in Figure 3.4.
The FEC depth and width is calculated based on 147mm² area of FEC. The area of FEC, $S_e$ is defined by equations 3.2, with the filling factor of motor, $\alpha$, and number of turn, $N_e$ set as 0.5 and 44 respectively.

$$N_e = \frac{J_e \alpha S_e}{I_e}$$  \hspace{1cm} (3.2)

Where $N_e$, $J_e$ (A/mm²), $\alpha$, $S_e$ (mm²), and $I_e$ (A) are number of turns, current density, filling factor, slot area and input current, respectively. Assuming only one water-jackets system is employed as a cooling system, the current density threshold is set to be 30A/mm², for FEC winding and the input current is set 50A as the maximum input current for FEC [71]. The FEC slot depth is one third of stator depth to give an appropriate distance between two FEC slot areas for the flux to flow in this area. FEC for the inner-rotor and outer-rotor HEFSM design contains two parts namely F1 and F2. Both parts inner and outer-rotor HEFSM for FEC1 and FEC2 is illustrated in Figure 3.5.

The armature coil depth and width are calculated based on 168mm² area of armature coil. The area of armature coil, $S_a$ is defined by equations 3.3, with the filling factor of motor, $\alpha$, and number of turn, $N_a$ set as 0.5 and 7 respectively.

$$N_a = \frac{J_a \alpha S_a}{I_a}$$  \hspace{1cm} (3.3)
Where $N_a$, $J_a$ (A/mm$^2$), $\alpha$, $S_o$ (mm$^2$) and $I_a$ (A$_{rms}$) are number of turns, current density, filling factor, slot area and input current, respectively. Assuming only one water-jackets system is employed as a cooling system, the current density threshold is set to be 30A/mm$^2$, for armature coil winding and the input current is set 360A$_{rms}$ as the maximum input current for FEC [71]. The depth of armature coil is set two third of the stator in order to avoid overlapping between armature coil winding and FEC winding. The direction of armature coil is shown in Figure 3.6 respectively. The direction of armature coils is in alternate direction.

![Figure 3.5: Direction of FEC](image)

(a) Inner-Rotor HEFSM (b) Outer-Rotor HEFSM

The design contains stator, rotor, armature coil, permanent magnet and FEC for inner-rotor and outer-rotor HEFSM uses the different materials. Stator and rotor use electrical steel 35H210 [69]. The armature coil and FEC use copper as their material. The PM material used for this motor is Neomax 35AH whose residual flux density and coercive force at 20°C are 1.2T and 932kA/m, respectively. Table 3.1 shows the material of the motor part.
REFERENCES


