A COMPARATIVE STUDY BETWEEN PMFSM AND HEFSM WITH IRON FLUX BRIDGES FOR HEV APPLICATIONS

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A COMPARATIVE STUDY BETWEEN PMFSM AND HEFSM WITH IRON FLUX BRIDGES IN HEV APPLICATIONS

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

Faculty of Electrical and Electronics Engineering
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For my beloved late mother and father
Che Anah bt Che Abdul Rahman and Jafar bin Samat,
My Siblings,
And my friends,
Thank you for your love, guidance and support
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I also would like to extend my gratitude to the Centre of Graduate Studies UTHM for their financial support during my studies. Besides, I take this opportunity to record my sincere thanks to all FSM members for their help and encouragement.

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I also place on record, my sense of gratitude to one and all who directly or indirectly, have lent their helping hand in this venture.
ABSTRACT

Nowadays, research and development of hybrid electric vehicles (HEVs) become popular in effort to reduce the pollutant emissions that can cause global warming due to demand of personal transportation. One example of successfully developed electric machines for HEVs is interior permanent magnet synchronous machines (IPMSMs). However, IPMSM design tends to be difficult because the permanent magnet (PM) is embedded in the rotor core and also the distributed armature winding. Therefore, a new machine known as flux switching machine (FSMs) which categorized in three groups is proposed with advantage of robust rotor structure which suitable for high speed applications. Thus, a new structure of 12S-10P PMFSM is introduced and investigated. However, this machine has some drawbacks and influence in term of performances, 12S-10P PMFSM have been transformed to 12S-10P and 12S-14P with additional FEC. In addition, iron flux bridges is introduced, due to the developed C-Type HEFSMs has a problem of separated stator core which lead to difficulty in manufacturing design as well as flux leakage to the outer stator. In this research, performance of PMFSM and HEFSM are analyzed and compared by 2D Finite Element Analysis (FEA) using JMag Designer ver.13.0, released by Japanese Research Institute (JRI). In order to achieve the target performance, deterministic optimization method is applied to improve the initial design. As a conclusion, HEFSM design has successfully achieved the target and power similar with IPMSM used in Prius ‘07 specifications. This machine can also be employed in motor with robust condition due to its high mechanical strength as well as high revolution speed such as a hybrid electric vehicle.
ABSTRAK

Pada masa kini, peyelidikan dan pembangunan terhadap kenderaan elektrik hibrid (HEVs) menjadi semakin popular dalam usaha untuk mengurangkan pelepasan bahan pencemar yang boleh mengakibatkan pemanasan global yang disebabkan oleh permintaan pengangkutan persendirian. Satu contoh mesin elektrik yang telah berjaya digunakan untuk kenderaan elektrik hibrid adalah mesin segerak magnet dalam kekal (IPMSMs). Walau bagaimanapun, rekabentuk IPMSM lebih cenderung menghadapi kesukaran kerana kedudukan magnet kekal (PM) yang terletak di dalam teras pemutar dan juga pengedaran angker penggulungan. Oleh demikian, satu mesin baru diperkenalkan, dikenali sebagai pensuisan fluks (FSM), dikategorikan kepada tiga kumpulan yang mempunyai kelebihan struktur pemutar teguh yang sesuai untuk aplikasi berkelajuan tinggi. Oleh itu, satu struktur baru iaitu 12S-10P PMFSM telah diperkenalkan dan dianalisis. Oleh kerana mesin ini mempunyai beberapa kelemahan dan ianya juga mempengaruhi dari segi persembahan, struktur 12S-10P PMFSM telah ditukar kepada 12S-10P dan 12S-14P dengan penambahan FEC. Di samping itu, jambatan fluks besi juga diperkenalkan, kerana rekaan C-Type HEFSMs yang mempunyai masalah teras pemegun terpisah justeru membawa kepada kesukaran dalam pembuatan rekabentuk dan juga kebocoran fluks pada pemegun luar. Dalam kajian ini, prestasi antara PMFSM dan HEFSM ini dijalankan oleh 2D-FEA iaitu JMAG Designer versi 13, dimana ianya dikeluarkan oleh Institut Penyelidikan Jepun (JRI). Dalam usaha untuk mencapai prestasi sasaran, kaedah pengoptimuman telah diguna pakai untuk penambahbaikan struktur permulaan. Kesimpulannya, rekabentuk HEFSM telah berjaya mencapai sasaran tork dan kuasa, iaitu menyamai IPMSM yang telah digunakan pada spesifikasi Prius ’07. Oleh yang demikian, mesin ini boleh digunakan kerana keadaan motor yang mantap disebabkan oleh kekuatan mekanikal yang tinggi dan juga kelajuan revolusi tinggi seperti kenderaan elektrik hibrid.
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<tr>
<td>A</td>
<td>Ampere</td>
</tr>
<tr>
<td>A_{rms}</td>
<td>Ampere root mean square</td>
</tr>
<tr>
<td>f_e</td>
<td>Electrical frequency</td>
</tr>
<tr>
<td>f_m</td>
<td>Mechanical rotation frequency</td>
</tr>
<tr>
<td>I_a</td>
<td>Armature current</td>
</tr>
<tr>
<td>J_a</td>
<td>Armature coil current density</td>
</tr>
<tr>
<td>J_e</td>
<td>FEC current density</td>
</tr>
<tr>
<td>k</td>
<td>natural entity</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>kW</td>
<td>kilowatt</td>
</tr>
<tr>
<td>L_a</td>
<td>motor stack length</td>
</tr>
<tr>
<td>L_{a-end}</td>
<td>estimated average length</td>
</tr>
<tr>
<td>L_e</td>
<td>motor stack length</td>
</tr>
<tr>
<td>L_{e-end}</td>
<td>estimated average length of end coil</td>
</tr>
<tr>
<td>mm</td>
<td>milimeter</td>
</tr>
<tr>
<td>Nm</td>
<td>Newton meter</td>
</tr>
<tr>
<td>N_a</td>
<td>number of turn of armature coil</td>
</tr>
<tr>
<td>N_{a-slot}</td>
<td>total number of armature coil slot in the motor</td>
</tr>
<tr>
<td>N_e</td>
<td>number of turn of FEC</td>
</tr>
<tr>
<td>N_{e-slot}</td>
<td>total number of FEC slot in the motor</td>
</tr>
<tr>
<td>N_r</td>
<td>Number of rotor poles</td>
</tr>
<tr>
<td>N_s</td>
<td>Number of stator slots</td>
</tr>
<tr>
<td>\rho</td>
<td>copper resistivity</td>
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<td>total copper loss</td>
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\[ P_e \] - FEC copper loss
\[ P_i \] - iron loss
\[ P_o \] - total output power
\( q \) - number of phases
\( A_g \) - Air gap
C1 - Configuration 1
C2 - Configuration 2
C3 - Configuration 3
C4 - Configuration 4
C5 - Configuration 5
C6 - Configuration 6
C7 - Configuration 7
emf - Electromotive force
DC - Direct current
V - Volt
EVs - Electric Vehicles
EMI - Electromagnetic-interference
FEC - Field Excitation Coil
FSM - Flux Switching Machine
HEFSM - Hybrid Excitation Flux Switching Machine
HEM - Hybrid Excitation Machine
HEVs - Hybrid Electric Vehicles
ICE - Internal Combustion Engine
IM - Induction Motor
IPMSM - Interior Permanent Magnet Synchronous Motor
JRI - Japanese Research Institute
mmf - Magnetomotive force
P - Pole
PM - Permanent magnet
PMFSM - Permanent Magnet Flux Switching Machine
PMSM - Permanent Magnet Synchronous Motor
S - Slot
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<td>Switch Reluctance Motor</td>
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CHAPTER 1

INTRODUCTION

1.1 Introduction

In over than hundred years, conventional vehicles operate on the principle of internal combustion engine (ICE) which based on fossil fuels have been used for personal transportation. Along with that, the demand of private vehicles has increased every day due to the increasing rates of rapid world populations. Due to the high demand and usage of personal vehicles, ICE automobile becomes a major source of the urban pollutions. Hence, the problems associated with ICE automobiles are three fold, environmental, economical, as well as political. One of the serious problems regarding to the environmental issue is the emissions. The environmental concerns can raise by the increasing pollution levels due to harmful emissions from hydrocarbon fuelled power sources [1-2]. Besides air pollution, the other main objection regarding ICE automobiles is the extremely low efficiency use of fossil fuel. In addition, some of the major challenges currently faced in the automotive industry are to reduce the dependency on fossil fuels, reduce the green house gases emitted per km of travel [3]. Government agencies and organizations have developed more stringent standards for the fuel consumption and emissions. Nevertheless, with the ICE technology being matured over the past 100 years, although it will continue to improve with the aid of automotive electronic technology, it will mainly rely on alternative evolution approaches to significantly improve the fuel economy and reduce emissions [4-5].

Therefore, in order to tackle these major issues, auto-manufacturers are shifting towards new technologies such as electric vehicles (EVs) and hybrid electric vehicles (HEVs). The concept of EV has been around since the early years of the
Since 1910, the EVs have been more numerous than vehicles with ICE. New environmental concerns over the amount of pollutants spilled into the atmosphere each day by ICE have become a powerful motivation for the use of EVs once again. EVs are some of the alternatives for future transportation. However, the major drawbacks of EVs are their limited range and high charging time. To overcome these drawbacks, HEVs which combine battery-based electric machines with an ICE is used. The concept of HEVs was conceived in the middle of the previous century. HEVs offer the most promising solutions to reduce the emission and the problem of limited range and inferior performance of EV [6-7].

Research in HEV development has focused on various aspects of design, such as component architecture, engine efficiency, reduced fuel emissions, materials for lighter components, power electronics, efficient motors, and high power density batteries. The primary motivations of this research are to increase the fuel economy and minimizing the harmful effects of the automobile to the environment. Except for gains in the fuel economy, HEVs also demonstrated a potential of reducing exhaust emission. For EVs and HEVs, the output characteristics of electric motors differ from those of ICEs. Typically, the electric motor eliminates the necessity to be idle at a stop, produce large torque at low speed, and offers a wide range of speed variations. It may be possible to develop lighter, more compact, more efficient systems by taking advantages of the characteristics of electric motors [8].

Selection of traction motors for hybrid propulsion systems is a very important step that requires special attention. In fact, the automotive industry is still seeking for the most appropriate electric-propulsion system for HEVs and even for EVs. In this case, key features are efficiency, reliability, and cost. The process of selecting the appropriate electric-propulsion systems is, however, difficult and should be carried out at the system level. In fact, the choice of electric-propulsion systems for HEVs mainly depends on three factors: driver expectation, vehicle constraint, and energy source. With these considerations, it is obvious that the overall motor operating point is not tightly defined [9]. Therefore, selecting the most appropriate electric propulsion system for HEV is a challenging task. Several examples of traction motor that have been applied for HEVs, such as direct current (DC) motor drives, induction motor (IM), switch reluctance motor (SRM) and permanent magnet synchronous
motor (PFSM) are demonstrated in Figure 2.1. The basic characteristics of an electric drive for HEVs are the following [10-11]:

(i) High torque and power density.
(ii) Very wide speed range, covering low-speed crawling and high-speed cruising.
(iii) High efficiency over wide torque and speed ranges.
(iv) Wide constant-power operating capability.
(v) High torque capability for electric launch and hill climbing
(vi) High intermittent overload capability for overtaking.
(vii) High reliability and robustness for vehicular environment.
(viii) Low acoustic noise.
(ix) Reasonable cost.
(x) High-efficiency generation over a wide speed range.
(xi) Good voltage regulation over wide-speed generation.

1.2 Problem statement

Interior permanent magnet synchronous machine (IPMSMs) using rare-earth permanent magnet is an example of successfully propulsion system employed for HEVs. It has been selected by the automobiles company due to the smaller size and lighter weight providing with design freedom of the vehicles and its higher efficiency contributing to less fuel consumption [12]. However, this machine also possess some disadvantages such as uncontrolled flux due to the constant PM flux, distributed armature winding resulting in much copper loss and high coil end length, and difficult to perform the design optimization due to complex shape and structure of IPMSM. As one option to overcome this problem, a new machine with flux switching operating principle namely permanent magnet flux switching machine (PMFSM) is introduced; which utilized permanent magnet as a flux source in stator [13]. However, this design has low performances in terms of torque and power while the flux source is difficult to regulate and also has a risk of high demagnetization. Thus, 12S-10P hybrid excitation flux switching machine (HEFSM) becomes as one of another alternative to increase the performances owing to the combination of flux
sources which consists of permanent magnet (PM) and field excitation coils (FECs) [14].

Various topologies of HEFSMs have been developed and investigated. The topology of 12S-10P C-Type HEFSM has an interest due to their simple and robust rotor design and high torque density. However, the developed C-Type has a problem of separated stator core which lead to difficulty in manufacturing design [15]. Hence, the fabrication process also becomes difficult due to the consistency of the stator shape. Moreover, the flux leakage will occur to the outer stator and extremity reduces the total performance of the machine. Thus, investigation of the additional iron flux bridge is introduced to overcome this problem.

1.3 Objectives

The objectives of this research are:

(i) To compare the electromagnetic performance between PMFSM and HEFSM topologies of 12S-10P machine.

(ii) To investigate the influences of flux bridge on stator and pole number in 12S HEFSM machine.

(iii) To obtain an optimum machine dimension for a desired rated performance.

1.4 Project scopes

The scopes of this research are:

(i) The design requirements, restrictions and specifications of the proposed machine for HEV applications are listed in Table 1.1. The electrical restrictions related with the inverter such as maximum 650V DC bus voltage and maximum 360V inverter current are set. The armature coil current density, $J_a$ and the FEC current density, $J_e$ is limit to 30 $A_{\text{rms}}/\text{mm}^2$ and 30 $A/\text{mm}^2$, respectively with the PM weight is set to 1.3kg. In addition, the target torque and power is set to 303Nm and 123kW, correspondingly.

(ii) Seven arrangements of iron flux bridges are introduced.

(iii) JMAG-Designer software version 13 is used to analyze the performances under no load analysis and load analysis.
Deterministic Optimization Method is used to improve the initial torque and power. Hence, sizing parameter such as stack length reduction, PM volume reduction with respects to PM width and PM height is introduced to the optimum design of 12S-14P HEFSM.

### Table 1.1: Design restrictions and target specifications of the proposed PMFSM and HEFSM [12]

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Proposed PMFSM and HEFSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. DC-bus voltage inverter (V)</td>
<td>650</td>
</tr>
<tr>
<td>Max. inverter current (A&lt;sub&gt;rm&lt;/sub&gt;)</td>
<td>360</td>
</tr>
<tr>
<td>Max. current density in armature coil, J&lt;sub&gt;a&lt;/sub&gt; (A&lt;sub&gt;rm&lt;/sub&gt;/mm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>30</td>
</tr>
<tr>
<td>Max. current density in FEC, J&lt;sub&gt;e&lt;/sub&gt; (A/mm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>30</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>269</td>
</tr>
<tr>
<td>Motor stack length (mm)</td>
<td>84</td>
</tr>
<tr>
<td>Air gap length (mm)</td>
<td>0.7</td>
</tr>
<tr>
<td>PM weight (kg)</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum torque (Nm)</td>
<td>303</td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>123</td>
</tr>
<tr>
<td>Iron flux bridge width (mm)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 1.5 Thesis outline

This thesis deals with a comparative study between permanent magnet flux switching machine (PMFSM) and hybrid excitation flux switching machine (HEFSM) for HEV applications. The thesis is divided into five chapters and the summary of each chapter are listed as follows:

(i) Chapter 1: Introduction

This chapter explains the introduction about the research, including the research background and the problems of IPMSM used in HEV. Then problems of current IPMSM used in HEV are highlighted and the research objectives are set to solve the problems. Besides, the project scopes of the research are included in this chapter.
(ii) Chapter 2: Literature review
In this chapter, the introduction of electric motors is discussed. Then, the introduction and classifications of flux switching machine including previous research and principle operation are discussed. In addition, the selected topology of PMFSM and HEFSM also clearly explains in this chapter.

(iii) Chapter 3: Methodology
This part describes the process of completing the proposed machine. These machines are examined using commercial 2D-FEA, JMAG-Studio ver. 13.0, released by JSOL Corporation. The process of this research can be divided into three phases including design process, performance analysis and optimization method.

(iv) Chapter 4: Results
This chapter discusses the results of this research which divided into four sections. Initially, the electromagnetic behaviour of 12S-10P C-Type PMFSM and HEFSM are investigated. However, the C-Type design has a problem of separated stator core which lead to difficulty in manufacturing process. Hence, iron flux bridge is introduced to overcome this problem. Then, the performances of 12S-10P HEFSM without and with iron flux bridges are investigated and compared. The third section analyzes the performance of various rotor pole studies i.e 12S-10P HEFSM and 12S-14P HEFSM with iron flux bridge. Since the initial performances of torque and power for both designs are far from target requirements of 303Nm and 123kW, respectively, design improvements using “deterministic optimization method” to treat several design parameters are conducted until the target performances are achieved. Then, the comparative performances of initial and final design for both designs are discussed. Lastly, the sizing parameter for 12S-14P HEFSM is introduced due to the optimum torque and power that obtained is more the target requirements. This study is divided into two cases, i.e stack length reduction and PM weight reduction. All performances for this study are discussed.

(v) Chapter 5: Conclusion and recommendations
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

This chapter clarifies the types of traction motor which has been used for HEVs. Flux switching machines (FSMs) are introduced, that is categorized in three groups. The operating principle of each FSMs is clearly discussed in this chapter. The overview of selected topologies of PMFSM and HEFSM are introduced.

2.2 Classification of traction motor

Among the different types of electric drives, there are four major types that are viable for HEVs, namely; DC machines, IMs, SRMs and PMSMs. They possess fundamentally different machine topologies, as shown in Figure 2.1.

2.2.1 DC machines

DC drives used to be widely accepted for HEVs. DC motors is prominent in electric propulsion, because their torque–speed characteristics suit the traction requirement. DC drives take the definite advantage of simple speed control, because of the orthogonal disposition of the field and armature MMFs. However, DC motor drives have a bulky construction, low efficiency, low reliability, and higher need of maintenance [16]. By replacing the field winding with PMs, the PM DC drives permit a considerable reduction in stator diameter, due to the efficient use of radial space.
Armature reaction is usually reduced, and commutation is improved, due to the low permeability of PMs. Although, the commutators and brushes attract a problem of DC drive, which makes them less reliable and unsuitable for a maintenance-free operation. The commutator, if used in proper operation, is a very rugged “inverter”. Therefore, the power electronics circuit can be kept relatively simple and at low cost. This is the case of the French automaker, PSA Peugeot Citroën, who introduced the HEV version of the well-known Berlingo, which is called Dynavolt, with a DC motor as electric propulsion [17].

Figure 2.1: Types of electric traction
(a)DC motors [16] (b) IMs [18] (c) SRMs [22] (d) PMSM [24]
2.2.2 Induction machines

Today, an IM drive is the most mature technology among various brushless motor drives [18]. Cage IMs are widely accepted as the most potential candidate for the electric propulsion of HEVs, owing to their mature technology, reliability, ruggedness. Not forgetting, their freedom of maintenance, low cost, high overall efficiency and ability to operate in hostile environments. They are particularly well suited for the rigors of industrial and traction drive environments. At a critical speed, the breakdown torque is reached. However, conventional control of induction drives, such as variable voltage variable frequency, cannot provide the desired performance. Any attempt to operate the motor at the maximum current beyond this speed will stall the motor. Moreover, efficiency at a high speed range may suffer, in addition to the fact that IMs efficiency is inherently lower than that of PM motors; it is due to the absence of rotor winding and rotor copper losses [19]. In addition, the development of EV and HEV induction machines is continually fuelled by new design approaches and advanced control strategies.

Generally, IM drives are having problems, such as high loss, low efficiency, low power factor and low inverter-usage. These problems pushed them out from the race of HEVs electric propulsion, which is more serious for the high speed and large power motor. Fortunately, these drawbacks is considered according to the available literature. Some researches propose takes these problems into action, in the design step of the IM used for HEVs. To improve the IM drives efficiency, a new generation of control techniques has been proposed. Some of the proposed techniques are particularly devoted to HEV applications, which constitute a progress, compared to the study made in [20-21].

2.2.3 Switch reluctance machines

SRMs are gaining much interest and have been recognized to have a potential for HEV applications. They have the definite advantages of simple construction, low manufacturing cost, fault-tolerant operation, and outstanding torque-speed characteristics. Even though this machine has a simple construction however, their design and control are difficult and subtle. Besides, this machine has disadvantages
of exhibit acoustic-noise problems torque ripple, special converter topology, excessive bus current ripple, and electromagnetic-interference (EMI) noise generation. Recently, fuzzy sliding mode control has been developed for the HEV SRMs to handle the machine nonlinearities and minimize the control chattering [22]. Additionally, an active vibration cancellation technique for the SRMs has been proposed, which induces an antiphase vibration to cancel a specified vibration mode. Hence, it reduced the acoustic noise. Nevertheless, SRMs is a solution that is actually envisaged for light and heavy HEV applications [23].

2.2.4 Permanent magnet synchronous machines

PMSM drives are becoming more and more attractive and can directly compete with the induction machines for HEVs. The advantages of the PMSM machines are highly efficiency, and have a high power density, and reliable. However, these motors inherently have a short constant-power region, due to their rather limited field weakening capability, resulting from the presence of the PM field (the fixed PM limit their extended speed range). In order to increase the speed range and improve the efficiency of PM brushless motors, the conduction angle of the power converter can be controlled at above the base speed. However, at a high-speed range, the efficiency may drop because of the risk of PM demagnetization [24]. Nevertheless, the key problem is their relatively high cost, due to PM materials.

There are various configurations of the PMSMs, which can be classified as surface PMSM (SPMSM) and interior PMSM (IPMSM). The latter is more mechanically rugged, due to the embedded PM in the rotor. Although, the SPMSM design uses fewer magnets than the IPMSM, both motors may achieve a higher air-gap flux density. Another configuration of PMSM is the PM hybrid motor, where the air-gap magnetic field is obtained from the combination of PM and DC FEC, as mentioned previously. In the broader term, PM hybrid motor may also include the motor whose configuration utilizes the combination of PMSM and SRM. Although the PM hybrid motor offers a wide speed range and a high overall efficiency, the construction of the motor is more complex than PMSM [25]. Table 2.1 briefly reviews the electric propulsion, which is recently adopted in the automotive industry.
Table 2.1: Electric propulsion adopted in the automotive industry [26]

<table>
<thead>
<tr>
<th>HEV Model</th>
<th>Propulsion System</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSA Peugeot-Citroën/Berlingo (France)</td>
<td>DC Motor</td>
</tr>
<tr>
<td>Renault/Kangaroo (France)</td>
<td>Induction motor</td>
</tr>
<tr>
<td>Chevrolet/Silverado (USA)</td>
<td>Induction motor</td>
</tr>
<tr>
<td>DaimlerChrysler/Durango (Germany/USA)</td>
<td>Induction motor</td>
</tr>
<tr>
<td>BMW/X5 (Germany)</td>
<td>Induction motor</td>
</tr>
<tr>
<td>Holden/ECOmodore (Australia)</td>
<td>Switch reluctance motor</td>
</tr>
</tbody>
</table>
In the last decade, Interior Permanent Magnet Synchronous Motors (IPMSM) has been extensively analyzed as feasible candidates for variable-speed HEV traction applications [27]. The IPMSM exhibits high efficiency when operating at constant speed in the constant-torque region, due to its lower copper losses. Besides, this IPMSM has been employed, mainly to increase the power density of the machines [28]. This can be proven by the historical progress in the power density of main traction motor installed on Toyota HEVs, as listed in Table 2.2. The power density of each motor employed in Lexus RX400h’05 and GS450h’06 have been improved approximately five times and more, respectively, compared to that installed on Prius’97 [29]. Although the torque density of each motor has been hardly changed, a reduction gear has been enabled, to elevate the axle torque. This is necessary for propelling the large vehicles such as RX400h and GS450h. As one of the effective strategies to increase the motor power density, the technological tendency to employ the combination of a high-speed machine and a reduction gear, would be accelerated.
Table 2.2: Historical progress in power density of main traction motor installed on Toyota Hybrid Electric Vehicles

<table>
<thead>
<tr>
<th>Model</th>
<th>Year</th>
<th>Max. Speed of Main Traction Motor (r/min)</th>
<th>Normalized Motor Power Density (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prius</td>
<td>2007</td>
<td>6000</td>
<td>1.0</td>
</tr>
<tr>
<td>Prius</td>
<td>2003</td>
<td>6700</td>
<td>1.75</td>
</tr>
<tr>
<td>RX400h</td>
<td>2005</td>
<td>12,400</td>
<td>4.86</td>
</tr>
<tr>
<td>GS450h</td>
<td>2006</td>
<td>14,400</td>
<td>5.61</td>
</tr>
</tbody>
</table>

Even though IPMSMs installed in HEV have good performances as well as being operated, this machine also possess some drawbacks, such as:

(i) The three-phase armature windings are wounded in the form of distributed windings, which results in much copper loss and high coil end length.

(ii) The mechanical stress of the rotor depends on the number of PM bridges. High number of bridges not only increases the mechanically weak points, but also causes much flux leakage between the PMs that will degrade the performance of the machine.

(iii) The present IPMSM has a complex shape and structure, which is relatively difficult to perform the design optimization.

(iv) The constant flux from PM is difficult to control, especially at light load high speed operating points.

(v) The volume of PM used in IPMSM is very high, more than 1.3kg, which increases the cost of the machine.

In order to avoid these drawbacks, a new structure is proposed, to build up the concentrated windings. It can reduce the copper loss and the coil end length, and robust rotor structure, which is suitable for high speed applications. In addition, this machine has a simple shape and ease for design optimization. Flux switching machine (FSM) with less rare-earth magnet is identified, and selected as an alternative candidate for HEV applications. FSM can be categorized into three groups such as Permanent Magnet Flux Switching Machine (PMFSM), Field Excitation Flux Switching Machine (FEFSM) and Hybrid Excitation Flux Switching Machine (HEFSM).
With significant achievements and improvements of permanent magnet materials and power electronics devices, the brushless machines excited by PM associated with FEC, which can be developed. This type is known as hybrid excitation machine (HEM) which combines both field excitation coil (FEC) and permanent magnet (PM) as a flux sources. HEM has several unique characteristics that are able to be applied in HEV drive system, which can be classified into four types, according to location of FEC and PM. The first type consists both FEC and PM are located at rotor side [30-32], the second type consists the FEC is in the stator, while the PM is in the rotor [33], the third type consists the FEC in the machine end while the PM is in the rotor [34-35] and the last category consists both FEC and PM are located in the stator [36-38]. The HEMs stated in three earliest types consists of a PM in the rotor and can be classified as “hybrid rotor-PM with FEC” whereas the final machine can be referred as “hybrid stator-PM with FEC”. The fourth machine, also known as HEFSM is getting more popular recently.

2.4 Introduction of flux switching machines (FSMs)

In the middle of 1950s, the concept of the FSM was founded and first published [39]. Over the last ten years or so, many novel and new FSM machine topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, to aerospace. FSM has been seen as a potential candidate for future variable speed applications because of its unique merits. FSM can be categorized into three groups, which are Permanent Magnet Flux Switching Machine (PMFSM), Field Excitation Flux Switching Machine (FEFSM) and Hybrid Excitation Flux Switching Machine (HEFSM). The classification of flux switching machines (FSMs) is shown in Figure 2.2.

![Diagram of Flux Switching Machines](image)
Excitation Flux Switching Machine (HEFSM) as shown in Figure 2.2. Permanent Magnet Flux Switching Machine (PMFSM), Field Excitation Flux Switching Machine (FEFSM) and Hybrid Excitation Flux Switching Machine (HEFSM).

### 2.4.1 Permanent magnet flux switching machine (PMFSM)

For several decade, PM machine have been studied, based on the principle of flux switching machine. Generally, such machines have a salient pole rotor and the PMs, which are housed in the stator. A three-phase FSM based on the homopolar flux principle and the bipolar flux principle have been described in [40-41] and [42-43], respectively, while a new type of single phase and three-phase PMFSM in which a pair of PMs is embedded on the stator were reported in [44] and [45], respectively. In addition, the performance of Law’s relay, a flux-switching type of limited angle actuator was proposed in [46]. Various examples of three-phase PMFSM are illustrated in Figure 2.3.

A three-phase of 12S-10P PMFSM is presented in Figure 2.3(a). This design has a salient pole stator core that 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 [42-43]. 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 such as A1, B1, C1, A2, B2 and C2 have the same winding configuration and are placed in the stator core to form 12 slots of windings. The salient pole rotor is similar to that of SRMs, which is more robust and suitable for high speed applications. 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. The heat is easy to dissipate from the stator, and the temperature rise in the magnet can be controlled by a proper cooling system.

Similar to the fractional-slot PM machine with none-overlapping windings, alternate poles wound windings can also be employed by the three-phase FSPM machine, in order to be fault-tolerant PMFSM [47] as shown in Figure 2.3(b).
Figure 2.3: Examples of PMFSM
(a) 12S-10P PMFSM (b) Fault Tolerance PMFSM (c) E-core PMFSM
(d) C-Core PMFSM (e) Outer rotor PMFSM
For this topology, the armature windings from Figure 2.3(a) are reduced by removing A2, B2 and C2 to form a total of six armature windings. In addition, this design gives the advantage of less copper loss, due the less usage of armature coil, but employed the similar quantity of PM. Nevertheless, the conventional PMFSM for both designs in Figure 2.3(a) and (b) have the demerit of high PM volume. The stator pole without armature winding in the Figure 2.3(b) is replaced by a simple stator tooth, in order to reduce the usage of PM, viz. the new E-core 12S-10P PMFSM is developed as in Figure 2.3(c) [48]. Besides, to form E-Core stator, half of the PM volume in Figure 2.3(b) is removed and the stator core is attached together. Further, the middle E-stator teeth can be removed to enlarge the slot area, and consequently the new C-core 6S-10P PMFSM is developed, as illustrated in Figure 2.3(d) [49]. It should be noted that the rotor pole number is close to the stator pole number in the conventional 12S-10P PMFSM, while it is close to twice of the stator pole number in the E- and C-core PMFSM. The 12S-22P outer-rotor PMFSM configurations illustrated in Figure 2.3(e), has been presented for in-wheel traction applications [50-51].

The general operating principle of the PMFSM is represented in Figure 2.4. As seen in figure, as example, the red arrows indicate the flux line of PM. Hence, at the position in Figure 2.4(a), the rotor pole aligns with one of two stator teeth over which a coil is wound, and the PM flux linked in the coil goes out of the stator and into the rotor pole. When the rotor moves forward to align with the other stator tooth belonging to the same coil shown in Figure 2.4(b), the flux goes out of the rotor pole and into the stator tooth, realizing “flux switching”, from which the name of flux switching of this motor is derived. Thus, as the rotor moves, the flux linkage in the windings will change periodically.

![Figure 2.4: Principle operation PMFSM](image-url)
2.4.2 Field excitation flux switching machines (FEFSM)

In conventional PMFSM, the PM excitation on the stator can be easily replaced by the DC excitation to form FEFSM as demonstrated in Figure 2.5. In other words, the FEFSM having salient-rotor structure is a novel topology, merging the principles of the inductor generator and the SRMs [52-53]. The idea of the FEFSM based on switching the flux linking polarity with the armature winding following the rotor position. All the motor windings are in stator slots and the rotor is a simple reluctance rotor. Figure 2.5(a) shows the simplest example 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. From the figure, it is clear that two armature coil and FEC windings are placed in the stator which overlapped each other. This design makes the FEFSM robust and easy to build due to the combination with SRM. As in all doubly salient motors, torque is developed by the movement of the rotor, with respect to the stator, to a position of minimum reluctance to the flux set up by current in the motor windings [54]. The novelty of the invention was that the single-phase AC configuration could be realized in the armature windings by the deployment of DC FEC and armature winding, to give the required flux orientation for rotation.

In addition, another example of single phase is demonstrated in Figure 2.5(b), is 8S-4P FEFSM with eight stator teeth and 4 rotor teeth. As seen in figure, it is obvious that four pole magnetic field is established when direct current is applied to the FEC winding in four of the slots. Meanwhile, the other four slots hold an armature winding that also pitched over two stator teeth. The direction of the current in the armature winding determines, so that a set of four stator poles carries flux and also the position of the rotor. As the FEC is excited by unipolar current, it can be directly connected in parallel, or in series with the DC-supply of power converter, which feeds the bipolar current into the armature winding. The design principle is explained in [55], and the single-phase 8S-4P FEFSM has achieved higher output power density, than the equivalent induction motor. Besides, the machine also achieved much higher efficiency, when compared with the IM. However, the single-phase machine has problems of low starting torque, large torque ripple, fixed rotating direction, and overlapped windings between armature coil and FEC.
Figure 2.5: Examples of FEFSM

(a) 1-phase 4S-2P FEFSM  (b) 1-phase 8S-4P FEFSM

(c) 3-phase 24S-10P FEFSM  (d) 3-phase 12S-10P FEFSM

(e) 3-phase 12S-8P segmental rotor FEFSM
The three phase 12S-10P is developed, as shown in Figure 2.5(c) and (d), due to achieve the desired performance of single phase. The 12S-10P FEFSM has been developed from 12S-10P PMFSM, 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 Figure 2.4(c) [56]. Similar to the PM polarity of 12S-10P PMFSM in Figure 2.3(a), this design consists of two flux sources, the FEC1 and FEC2 that arranged in alternate DC current source polarity to generate two flux polarities. However, the total flux generation is limited due to the isolated and unused stator teeth, and thus, affecting the performances of machine. Nonetheless, several structures and performances of FEFSM for various applications have been investigated in [57-58]. Regardless, another three phase machine of 12S-10P FEFSM is shown in Figure 2.5(d) [59]. This combination has been chosen because it can be considered as the best minimum combination of slot-pole. It is to avoid odd rotor pole numbers, such as 6Slot-5Pole and 6Slot-7Pole machines, that yields unbalanced pulling force. In addition, this combination is proposed to avoid high torque ripples, in case of 6Slot-8Pole and 6Slot-4Pole machines. Besides, this machine has an advantage to take good balance between rotor and stator pole widths for minimizing inescapable torque pulsation.

Since all FEFSM explained above posses an overlap winding between FEC winding and AC winding, which caused higher coil end length, a 12S-8P FEFSM with segmental rotor is proposed as shown in Figure 2.5(e) [60]. Segmental rotor has the ability to provide magnetic path for transmitting the field flux to nearby stator armature coil, with respect to rotor position. In addition, this design presents shorter end windings with non overlapping coil, when compares to salient rotor arrangement having overlapping coils. It has considerable gains, due to the reason that it utilizes less conductor materials, and has further improvement in overall machine efficiency [61].

Figure 2.6 shows the operating principle of the FEFSM, in which a field flux path generated by an mmf of FEC at different particular two rotor positions when the FECs are energized with DC current. The line with arrows depicts the field flux path. The direction of the FEC fluxes into the rotor is demonstrated in Figure 2.6(a) and (b), respectively while the direction of FEC fluxes into the stator is represented in Figure 2.6(c) and (d), correspondingly to produce a complete one cycle flux. The
flux linkage of FEC switches its polarity by following the movement of salient pole rotor, which creates the word “flux switching” that is similar with PMFSM. Each reversal of armature current shown by the transition between Figure 2.6(a) and (b), causes the stator flux to switch between the alternate stator teeth. The flux does not rotate, but shifts clockwise and counterclockwise with each armature-current reversal. With rotor inertia and appropriate timing of the armature current reversal, the reluctance rotor can rotate continuously at a speed controlled by the armature current frequency. The armature winding requires an alternating current reversing in polarity in synchronism with the rotor position. For automotive applications the cost of the power electronic controller must be as low as possible. This is achieved by placing two armature coils in every slot, so that the armature winding comprises a set of closely coupled (bifilar) coils [62].

Figure 2.6: Principle operation 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
2.4.3 Hybrid excitation flux switching machines (HEFSM)

PMFSM has attracted a lot of attention over the last two decades, due to their high torque density and outstanding robustness [63-64]. In order to improve the flux-weakening capability of this kind of machine, and to extend their application range to hybrid vehicles, various topologies of HEFSM have been developed [65-67]. HEFSM combines the advantages of PM excitation by PMs which utilize primary excitation, whereas DC FEC as a secondary source. In order to get a high density synchronous machine with good flux control, both excitations is combined. Conventionally, PMFSMs can be operated beyond base speed in the flux weakening region, by means of controlling the armature winding current. By applying negative d-axis current, the PM flux can be counteracted, but with the disadvantage of increase in copper loss and reduce the efficiency, reduce power capability, and also possible irreversible demagnetization of the PMs. 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 [68-70]. Because of the additional excitation windings, flux enhancing and weakening operations become much easier, which makes the HEFSM a well-suitable choice for HEVs [71].

Figure 2.7 presents the various combination of slot-pole for HEFSM that have been developed. Figure 2.7(a) shows a 6S-4P HEFSM that was proposed in [72]. However, as seen in figure, this design has low torque density and long end winding for FEC. In addition, both machines have overlapped armature windings, and can increase copper loss. Meanwhile, another HEFSM is illustrated in Figure 2.7(c). This machine is a 3 phase 12S-10P PMFSM, which slot in with the FEC at the outer stator. Hence, this machine employing non overlapping field and armature windings was proposed in [73]. However, the outer diameter of the machine is significantly enlarged for the field winding, which significantly reduces torque density. In addition, the magnets in the PMFSM can be partially replaced by the DC excitation windings. Consequently, several hybrid-excited topologies were developed [74] as shown in Figure 2.7(c), albeit they have overlapping armature and field windings, with significantly reduced torque capability. The foregoing hybrid-excited machines with magnets on the stator also suffer from one of these three disadvantages.
(i) The DC FEC is in series with the field excited by PMs, which limits the flux adjusting capability due to low permeability of the PM, Figure 2.7(a).

(ii) The flux path of DC FEC significantly reduces the main flux excited by magnets and even short circuits the magnet flux, Figure 2.7(c) and (d).

(iii) Torque density may be significantly reduced, due to less PM volume, Figure 2.7(c) and (d).

Therefore, a new 6S-10P E-core HEFSM is proposed, which is redesign from 12S-10P E-core PMFSM machine to eliminate the foregoing disadvantages, as shown in Figure 2.7(d). As seen in figure, this machine is inserted with the DC FEC on the middle teeth of the E-core stator. Additionally, it employs non overlapping field and armature windings and exhibits a simple structure. Other than that, the volume of magnet E-core HEFSM is kept maintain as same with the conventional E-core PMFSM. Nevertheless, Figure 2.7(e) [75] presents a 12S-10P PMFSM with additional excitations with theta direction, in order to provide further attractive characteristics. However, this machine has a limitation of torque and power production in high current condition, due to insufficient stator yoke width between excitation coil and armature coil slots resulting in magnetic saturation and negative torque production as discussed in [76-77]. Nonetheless, after some design refinements and improvements especially on the yoke mentioned above and coil area, this machine is capable of operating with desired performance. As the other infirmity of this machine due to high pole-pair number, the PWM frequency required for HEV application is very high, compared to the original frequency used in IPMSM. Therefore, the original design has been transformed as 6-slot 5-pole machine, to reduce PWM frequency similar to the implementation in conventional 8-pole IPMSM drive.

However, to overcome the drawback in Figure 2.7(e), another topology of 12S-10 HEFSM with radial direction is proposed [78], as shown in Figure 2.7(f). The FEC on this machine is wounded in radial direction on the stator to eliminate the flux cancellation effect in HEM, thus can increase the total torque production. In addition, the outer rotor version of the machine, Figure 2.7(g), has been proposed for direct drive electric vehicle applications [79-80]. Although the outer-rotor configuration machine is capable of providing higher torque density and efficiency, there is very limited reports have been published for FSM, if compared to the inner-rotor.
Figure 2.7: Examples of HEFSM
(a) 6S-4P HEFSM  (b) 12S-10P Outer FEC HEFSM  (c) 12S-10P E-core HEFSM
(d) 12S-10P HEFSM Theta Direction  (e) 12S-10P HEFSM Radial Direction
(f) 12S-10P Outer Rotor HEFSM
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