DESIGN STUDY OF HYBRID EXCITATION FLUX SWITCHING MOTOR FOR ELECTRIC VEHICLES

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Specially dedicated to:

My beloved husband, **Suwardifitri Bin Said**

My lovely sweet little girl, **Saidatul Nurina Aulfiah**

DEAR, thank you so much for always be by my side and being so supportive

Thank you for your unpaid sacrifices

I love you forever

My Family

Thank you for everything

My valuable friends, course mates and workmates;

Akma, Kak Zira, Kak Ayu, Aty, Kak Nani and unmentioned individuals

Thanks for being so supportive and thanks for the advices and prayers

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ABSTRACT

Hybrid excitation flux switching motor (HEFSM) is an attractive features compared to interior permanent magnet synchronous motor (IPMSM). The hybrid excitation is applied in this project to gain the high torque of the system. This is because the flux was achieved from both permanent magnet and field excitation coil. The design of 6 slot 7 pole inner rotor hybrid excitation motor is analyse by using the JMAG Designer Software which is a simulation software that easily utilized by the user. The analysis of no load, with load and improvement of the motor design is done. The objective of the project of obtaining 207 Nm torque of the motor is succesful since the improvement of the design give the torque of 228.70 Nm at speed 9161r/min from the initial torque of 171.04 Nm at speed 12580r/min. The performance of motor is also improved when the maximum power is increase from 155kW to 173kW. The characteristic represent the high torque, low speed motor performance. An improved design is to gain a better performance in its maximum torque and power production. As the design results, the improved motor enables to keep the better power density in the initial design.

ABSTRAK

Hybrid excitation flux switching motor (HEFSM) mempunyai ciri-ciri yang menarik berbanding *interior permanent magnet synchronous motor (IPMSM)*. Pengujaan hibrid digunakan dalam projek ini untuk menghasilkan tork yang tinggi bagi sistem. Ini kerana fluks dicapai dari kedua-dua magnet kekal dan medan pengujaan gegelung. Reka bentuk 6 slot 7 pole rotor dalaman pengujaan hibrid motor dianalisis menggunakan Designer Software JMAG yang merupakan perisian simulasi yang mudah digunakan oleh pengguna. Analisis tanpa beban, dengan beban dan peningkatan reka bentuk motor itu dilakukan. Objektif projek memperoleh tork motor 207 Nm tercapai kerana peningkatan reka bentuk memberikan tork 228,70 Nm pada kelajuan 9161r/min berbanding tork permulaan 171,04 Nm pada kelajuan 12580r/min. Prestasi motor juga bertambah baik apabila kuasa maksimum mengalami peningkatan dari 155kW kepada 173kW. Ciri ini memberikan prestasi motor dalam keadaan tork yang tinggi pada kelajuan rendah. Peningkatan reka bentuk adalah untuk mendapatkan prestasi yang lebih baik dalam tork dan kuasa pengeluaran maksimum. Motor dalam reka bentuk ini bertambah baik dan mempunyai ketumpatan kuasa yang lebih baik berbanding reka bentuk awal.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A demand for vehicles using electrical propulsion drives is getting higher and higher from the stand points of preventing global warming and saving fossil fuel recently. As one of the vehicles, many automotive companies have commercialized Hybrid Electric Vehicles (HEVs) in which Interior Permanent Magnet Synchronous Motors (IPMSM) have been employed as a main traction motor in terms of high torque and/or power density, and high efficiency over most of operating torque-speed range [1] . This is due to the restriction of motor size to ensure enough passenger space and the limitation of motor weight to reduce fuel consumption. As one of effective strategies for increasing the motor power density, the technological tendency to employ the combination of a high-speed machine and a reduction gear would be accelerated.

With the significant achievements and improvements of permanent magnet materials and power electronics devices, the brushless machines excited by PM associated with FEC are developing dramatically. This type of machine is called hybrid excitation machine (HEM) that can be classified into four categories. The first type consists of both PM and FEC at rotor side such as combination rotor hybrid excitation (CRHE) machine and synchronous/PM hybrid AC machine. The second type consists of PM in the rotor while FEC is in the stator. The third type consists of PM in the rotor while the FEC is in the machine end. Finally, the fourth type of HEM is the machine, which has both PM and FEC in the stator. It should be emphasized that all HEMs mentioned in the first three have a PM in the rotor and can be categorized as “hybrid rotor-PM with field excitation machines” while the fourth machine can be referred as “hybrid stator-PM with field excitation machines”. Based on its principles of operation, the fourth machine is also known as “hybrid excitation flux switching machine (HEFSM)” which is getting more popular recently [2]- [3].

In this study, a 6S-7P HEFSM in which the arrangement of FEC in radial direction is proposed for HEV applications. The proposed machine is composed of 6 PMs and 6 FECs distributed uniformly in the midst of each armature coil. The three-phase armature coils are accommodated in the 6 slots for each 1/3 stator body periodically. As the rotor rotates, the fluxes generated by PMs and mmf of FECs link with the armature coil alternately. Generally, the relation between the mechanical rotation frequency and the electrical frequency for this machine can be expressed as: $f_e = Nr.f_m$

where fe is the electrical frequency, f_m is the mechanical rotation frequency and Nr is the number of rotor poles respectively. The presence of excitation coil makes these types of machines more attractive in terms of modulating the PM flux.

1.2 Problem statement

Hybrid excitation machines (HEMs) consist of permanent magnet (PM) and field excitation coil (FEC) as their main flux sources. It has several attractive features compared to interior permanent magnet synchronous machines (IPMSM) which conventionally employed in hybrid electric vehicles (HEVs). Among various types of HEM, the machine with both permanent magnet and excitation coil located on the stator has the advantage of robust rotor structure similar as switch reluctance machine (SRM) and make this machine to be applied for high speed motor drive systems.

1.3 Objectives

The objectives of this study are:

i. To design the 6S-7P HEFSM inner rotor motor.
ii. To analyze the performance of the designed motor under no load condition, with load condition, the torque, power and speed of the motor.
iii. To improve the performance of initial design of 6S-7P HEFSM.

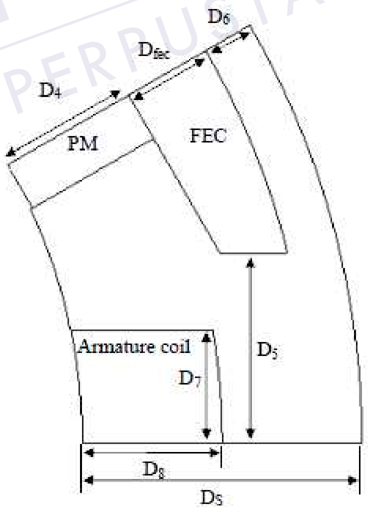
1.4 Scopes

The design of 6S-7P motor is by using the JMAG Designer Software. JMAG Designer is the electromagnetic simulation software than be easily utilized by the user because of its CAD like usability. Application of CAD data makes it possible to introduce magnetic field analysis into the existing design process.

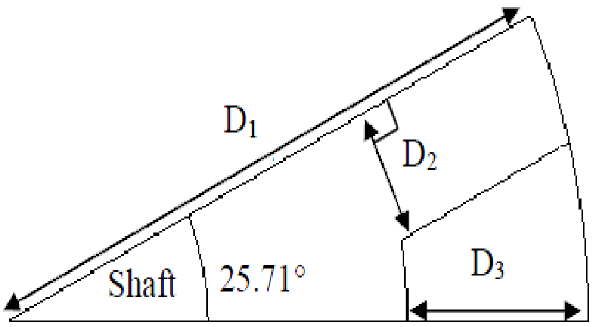
By using the parameter as in Table 1.1 and Figure 1.1(a) and (b), the designing of 6S-7P motor is made in the Geometry Editor of the JMAG Designer. The drawing process take place with the specification needed.

Table 1.1: Parameters of Design 6S-7P HEFSM

D1	Rotor inner radius(mm)
D2	Rotor pole depth(mm)
D3	Rotor pole width(mm)
D4	PM length (mm)
D5	Excitation coil pitch(mm)
D6	Stator outer core thickness(mm)
D7	AC width(mm)
D8	AC height(mm)



(a) Design of stator



(b) Design of rotor

Figure 1.1: The geometry of 6S-7P motor (a) Stator (b) Rotor

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Electric Motor

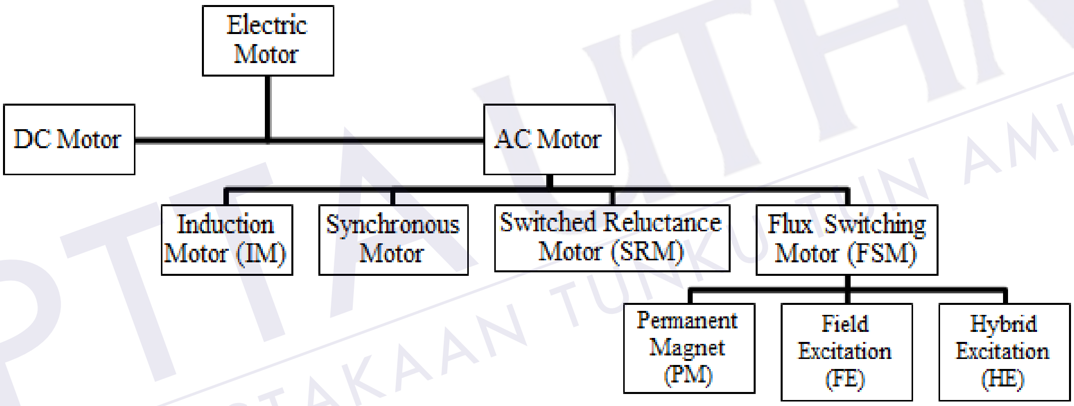


Figure 2.1: Types of Electric Motors

An electric motor is an electrochemical device that converts electrical energy into mechanical energy. Most electric motors operate through the interaction of magnetic and current-carrying conductor to generate force. Electric motors may be classified by the source of electric power, by their internal construction, by their application, or by the type of motion they give. As shown in Figure 2.1, electric motor can be divided into several types which have their own advantages and disadvantages.

2.2 Classification of Flux Switching Motor (FSM)

Generally, the FSMs 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 PM and FE has only Permanent Magnet and Field Excitation Coil (FEC), respectively as their main flux sources, while HE combines both PM and FEC as their main flux sources. Figure 2.2 illustrates the general classification of FSMs.

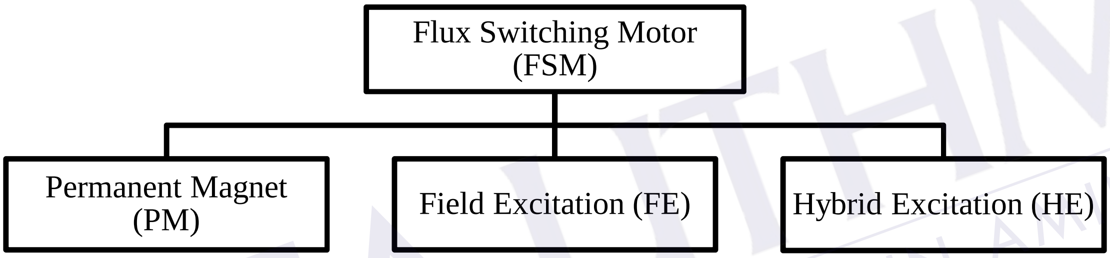


Figure 2.2: General Classification of FSM

2.2.1 Permanent Magnet Flux Switching Motor (PMFSM)

PM motors based on the principle of flux switching have been studied for several decades. Generally, such motors have a salient pole rotor and the PMs which are housed in the stator. 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.

The general operating principle of the PMFSM is illustrated in Figure 2.3, where the black arrows show the flux line of PM as an example. From the figure, when the relative position of the rotor poles and a particular stator tooth are as in Figure 2.3 (a), the flux-linkage corresponds to one polarity. However, the polarity of the flux-linkage reverses as the relative position of the rotor poles and the stator tooth changes as shown in Figure 2.3(b), which the flux linkage switches polarity as the salient pole rotor rotates.

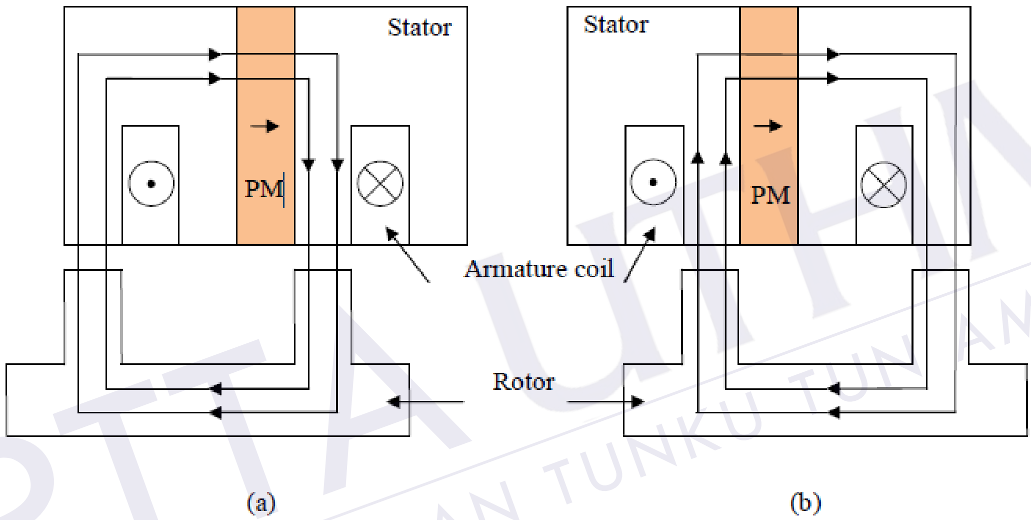


Figure 2.3: Principle Operation of PMFSM

2.2.2 Field Excitation Flux Switching Motor (FEFSM)

FEFSM is a form of salient-rotor reluctance motor with a novel topology, combining the principles of the inductor generator and the SRMs [4]- [5]. The concept of the FEFSM involves changing the polarity of the flux linking with the armature winding, with respect to the rotor position. The viability of this design was demonstrated in applications requiring high power densities and a good level of durability [6]- [7]. 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.

The operating principle of the FEFSM is illustrated in Figure 2.4. Figure 2.4(a) and (b) show the direction of the FEC fluxes into the rotor while Figure 2.4(c) and (d) illustrate the direction of FEC fluxes into the stator which produces a complete one cycle flux. Similar 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 2.4(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. 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 [8]- [9].

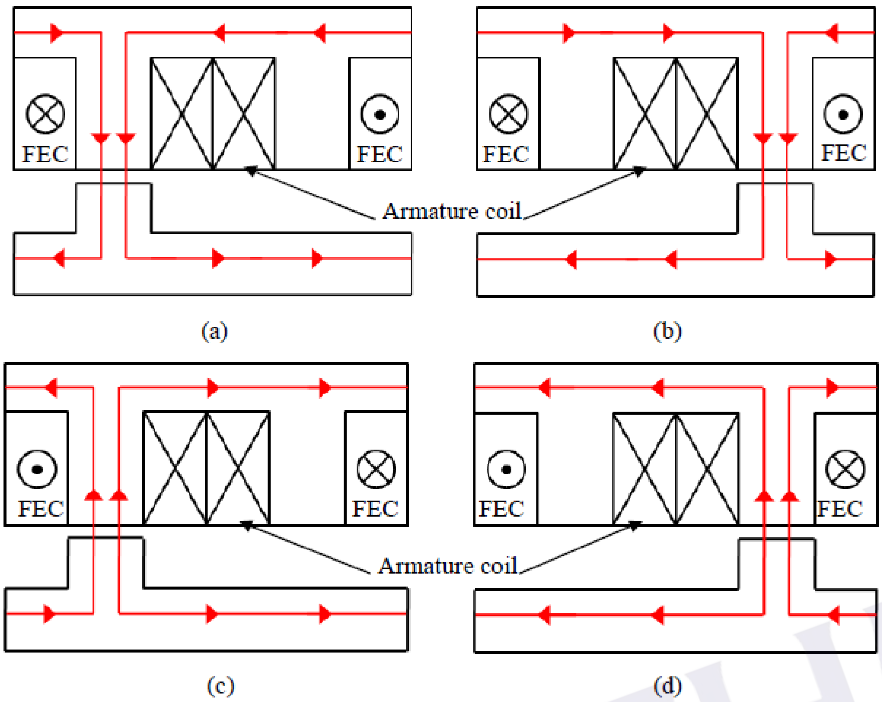


Figure 2.4: Principle operation of FEFSM (a) θ*e*=0° and (b) θ*e*=180° flux moves from stator to rotor (c) θ*e*=0° and (d) θ*e*=180° flux moves from rotor to stator

2.2.3 Hybrid Excitation Flux Switching Motor (HEFSM)

Hybrid excitation flux switching motors (HEFSMs) are those which utilize primary excitation by PMs as well as DC FEC as a secondary source. Conventionally, PMFSMs can be operated beyond base speed in the flux weakening region by means of controlling the armature winding current. HEFSM is an alternative option where the advantages of both PM motors and DC FEC motors 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 [10]- [11].

The operating principle of the proposed HEFSM is illustrated in Figure 2.5, where the red and blue line indicate the flux from PM and FEC, respectively. In

Figure 2.5(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 2.5(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. As one advantage of the DC FEC, the flux of PM can easily be controlled with variable flux control capabilities as well as under field weakening and or field strengthening excitation. The advantages and disadvantages of FSM discussed in this chapter are listed in Table 2.1.

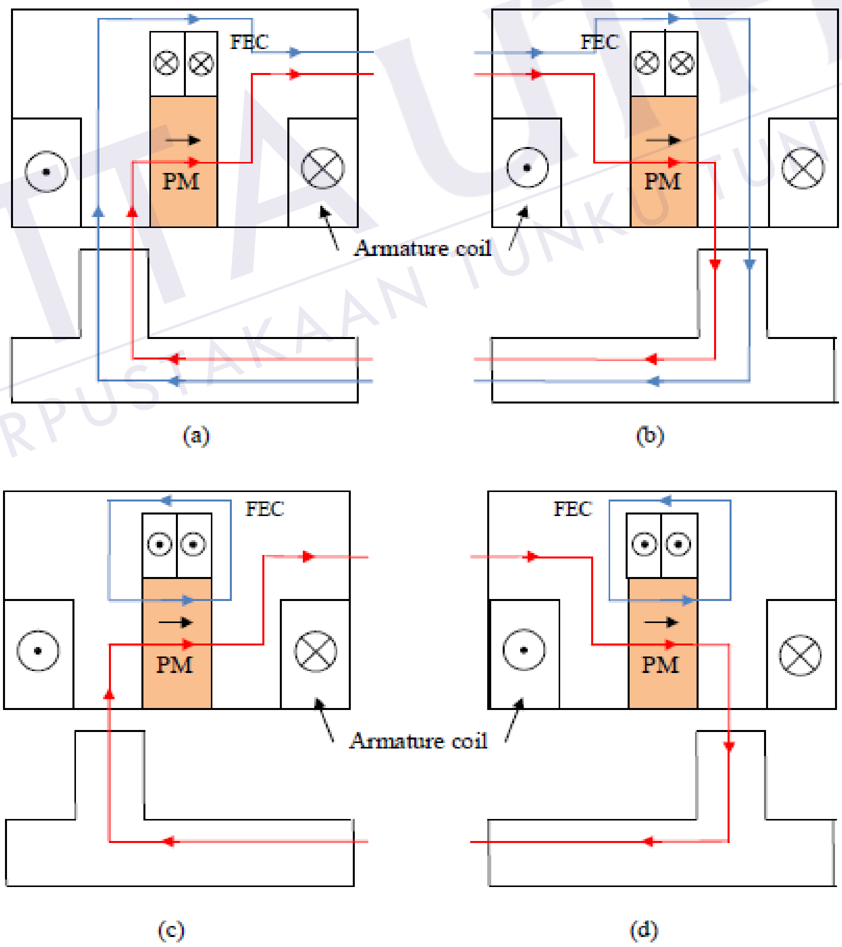


Figure 2.5: The operating principle of the proposed HEFSM (a) θ*e*=0° - more excitation (b) θ*e*=180° - more excitation (c) θ*e*=0° - less excitation (d) θ*e*=180° - less excitation.

Table 2.1: Advantages and disadvantages of FSM

Advantages	Disadvantages
1. Simple and robust rotor structure suitable for high speed applications 2. (Easy to manage magnet temperature rise as all active parts are located in the stator 3. Flux focusing / low cost ferrite magnets can also be used 4. Sinusoidal back-emf waveform which is suitable for brushless AC operation	1. Reduced copper slot area in stator 2. Low over-load capability due to heavy saturation 3. Complicated stator 4. Flux leakage outside stator 5. High magnet volume for PMFSM

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology of this research is by using JMAG-Designer version 13.0 software to design the motor. JMAG is simulation software for the development and design of electrical devices. JMAG was originally release in 1983 as a tool to support design for devices such as motors, actuators, circuit component, and antennas. The design of 6S-7P HEFSM is divide into two parts which is by using Geometry Editor and it is continued by using JMAG-Designer. The work flow of the geometry editor and JMAG-Designer are illustrated in Figure 3.2(a) and (b) respectively.

To design a motor, there are some restrictions and specifications need to follow. This is to ensure the designed motor will be around the recommended details, thus the output performance as requested is achieved. The summary of overall restrictions and specifications are as shown in Table 3.1. The Figure 3.1 shows the design of 6S-7P Inner Rotor HEFSM. The dimension of the motor is shown in Figure 3.3. All these requirements are need in designing the motor.

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