PERFORMANCE STUDIES OF HEFSM WITH 6 SLOT- 7 POLE FOR HEV APPLICATION

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ABSTRACT

Hybrid excitation machines (HEMs) that consist of permanent magnet (PM) and field excitation coil (FEC) as their main flux sources has several attractive features compared to interior permanent magnet synchronous machines (IPMSM) conventionally employed in hybrid electric vehicles (HEVs). Hybrid excitation flux switching machines (HEFSM) is one type of HEMs. This project is to decrease the PM size in a HEFSM so that the cost of the machine can be reduce. By reducing the size of PM, the torque and the power of the machine will be slightly different from the original PM size. The torque and other specification will be seen in the results.

ABSTRAK

Hybrid excitation machines (HEMs) yang terdiri daripada magnet kekal (PM) dan *field excitation coil* (FEC) sebagai sumber utama fluks mempunyai beberapa ciri menarik berbanding *interior permanent magnet synchronous machines* (IPMSM) konvensional yang digunakan dalam kenderaan elektrik hibrid (HEVs). *Hybrid excitation flux switching machines* (HEFSM) adalah salah satu jenis HEMs. Projek ini adalah untuk mengurangkan saiz PM di dalam HEFSM supaya kos mesin boleh dikurangkan. Dengan mengurangkan saiz PM, daya kilas dan kuasa mesin akan berbeza sedikit daripada masin yang mempunyai saiz PM asal. Daya kilas dan spesifikasi lain akan dilihat dalam keputusan projek ini.

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LIST OF SYMBOLS AND ABBREVIATIONS

HEMs	-	Hybrid Excitation Machines
PM	-	Permanant Magnet
FEC	-	Field Excitation Coil
IPMSM	-	Interior Permanent Magnet Synchronous Machines
HEVs	-	Hybrid Electric Vehicles
HEFSM	-	Hybrid Excitation Flux Switching Machines
PMFSM	-	Permanent Magnet Flux Switching Machines
IM	-	Induction Motor
SM	-	Synchronous Motor
SRM	-	Switched Reluctance Motor
EMI	-	Electromagnetic-interference
FEFSM	-	Field Excitation Flux Switching Synchronous Machine
HEFSM	-	Hybrid Excitation Flux Switching Synchronous Machine
AC	-	Armature Coil

CHAPTER 1

INTRODUCTION

1.1 Introduction:

The demand for electrical propulsion drives vehicles is getting higher to replace fossil fuel vehicles. The automotive companies in Malaysia had started to design a new type of vehicle called Hybrid Electric Vehicles (HEV) in which an electric motor is incorporated to the vehicles alongside the usage of fossil fuel engine.

Hybrid excitation flux switching machines (HEFSM) are those which utilize primary excitation by permanent magnets (PM) as well as DC field excitation coil (FEC) as a secondary source in an electric motors [1]. Permanent magnet flux switching machines (PMFSM) have relatively poor flux weakening performance but 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 field 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 DCFEC 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 [2-4].

Various combinations of stator slot and rotor pole for HEFSM have been developed. For example, a 6S-4P, 6S-5P, and 6S-7P model, most of the PM flux flows into the stator iron around the FEC, while 100% flux of PM flows around the FEC for 6S-8P model. This will give advantages of less cogging torque and almost no back-emf at open-circuit condition [5-6].

1.2 Problem statement:

6S–7P HEFSM has been design and optimized with the torque of 342.0 Nm and the power of 130.9 kW. Since the value of PM used in this structure is consider high, with 1.1 kg, the cost of the machine will also be high. Thus, a study on reduction of PM value will be carried out through this research with the target of cost reduction while maintaining the same performance.

1.3 Objectives:

The objectives of this research are:

i. To design a 6S-7P HEFSM.
ii. To analyze the performance of HEFSM.
iii. To investigate the performance of HEFSM of less PM value.

1.4 Scope:

The design restrictions and target specifications of the proposed machine are listed in Table I. The table includes the available and estimated specifications of the HEFSM. The outer diameter, the shaft radius and the air gap of the main part of the machine design being 264mm, 30mm and 0.8mm respectively. Under these restrictions, the weight of the PM is set to be 1.1kg [1].

The target maximum torque of 342Nm, the target maximum power is set to be more than 130kW, resulting in that the proposed machine promises to achieve similar to that estimated of HEFSM. Commercial FEA package, JMAG-Studio ver.12, released by Japanese Research Institute (JRI) is used as 2D-FEA solver for this design. The PM material used for this machine is NEOMAX 35AH whose residual flux density and coercive force at 20^{o}C are 1.2T and 932kA/m, respectively while the electrical steel 35H210 is used for rotor and stator body [3].

Table 1: HEFSM Design Restrictions and Specifications

Items	6S-7P HEFSM
Max. DC-bus voltage inverter (V)	650
Max. inverter current (A_{rms})	360
Max. current density in armature winding, J_a (A_{rms}/mm^2)	30
Max. current density in excitation winding, Je (A/mm^2)	30
Stator outer diameter (mm)	264
Motor stack length (mm)	70
Shaft radius (mm)	30
Air gap length (mm)	0.8
PM weight (kg)	1.1
Maximum speed (r/min)	12400
Maximum torque (Nm)	333
Reduction gear ratio	2.478
Max. axle torque via reduction gear (Nm)	825
Max. power (kW)	>123
Power density (kW/kg)	>3.5

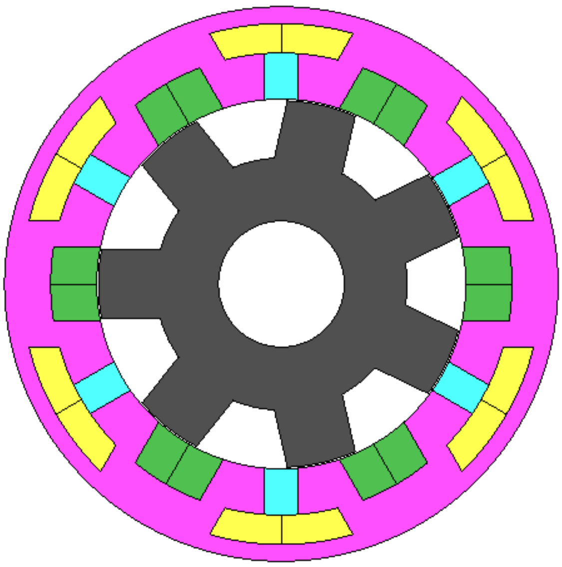


Figure 1.1: Design of a 6S-7P HEFSM

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of electric motor

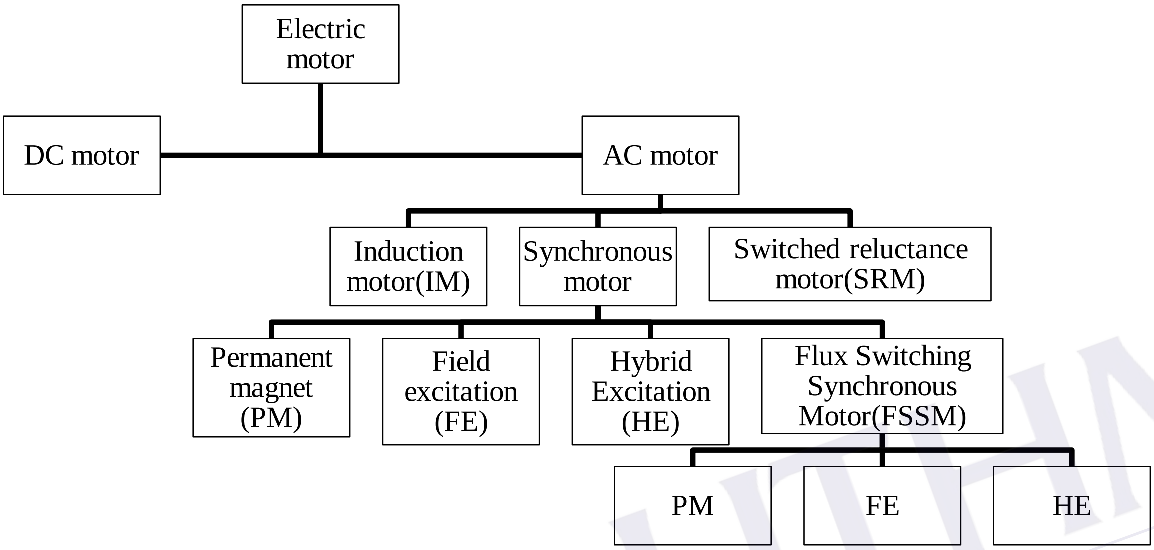


Figure 2.1 Electric motor analysis

An electric motor is an electrochemical device that converts electrical energy into mechanical energy [1]. 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 [4].

2.2 Review on Electric Motors Used In HEV

At present, the major types of electric motors under serious consideration for HEVs as well as for EVs are the dc motor, the induction motor (IM), the permanent magnet synchronous motor (SM), and the switched reluctance motor (SRM) [5]. Moreover, based on the exhaustive review on state of the art of electric-propulsion systems, it is observed that investigations on the cage IMs and the SM are highly dominant, whereas those on dc motors are decreasing but SRMs are gaining much interest [6-9]. The major requirements of HEVs electric propulsion, as mentioned in past literature, are summarized as follows:

(i) high instant power and high power density
(ii) high torque at low speed for starting and climbing, as well as high power at high speed for cruising
(iii) very wide speed range, including constant-torque and constant-power regions
(iv) fast torque response
(v) high efficiency over the wide speed and torque ranges
(vi) high efficiency for regenerative braking
(vii) high reliability and robustness for various vehicle operating conditions
(viii) reasonable cost

Moreover, by replacing the field winding with permanent magnet (PM), the PM dc machines permit a considerable reduction in the stator diameter due to the efficient use of radial space. Since dc motor requires high maintenance mainly due to the presence of the mechanical commutator (brush), as the research advances the brushes are replaced with slippery contacts. Nevertheless, dc motor drives have a few demerits such as bulky construction, low efficiency and low reliability.

Today, an IM drive is the most mature technology among various brushless motor drives. Cage IMs are widely accepted as the most potential candidate for the electric propulsion of HEVs, due to their reliability, ruggedness, low maintenance, low cost, and ability to operate in hostile environments [6-7]. However, the presence of a breakdown torque at the critical speed, limits its extended constant-power operation. Any attempt to operate the motor at the maximum current beyond the critical 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 PMSM, due to the presence of rotor winding and rotor copper losses [5].

Meanwhile, SRMs are gaining much interest and are recognized to have a potential for HEV applications. These motors have definite advantages such as simple and rugged construction, low manufacturing cost, fault-tolerant operation, simple control, and outstanding torque-speed characteristics. Furthermore, SRM can inherently operate with an extremely long constant-power range. However, several disadvantages for HEV applications outweigh the advantages. They are acoustic noise generation, torque ripple, necessity of special converter topology, excessive bus current ripple, and electromagnetic-interference (EMI) noise generation.

On the other hand, PMSMs are becoming more and more attractive and most capable of competing with other motors for the electric propulsion of HEVs. In fact, they are adopted by well-known automakers such as Toyota, Honda, etc., for their HEVs. These motors have many advantages. The overall weight and volume are significantly reduced for a given output power, and it has high power density, high efficiency and high reliability. In addition, the heat generated can be efficiently dissipated to the surroundings. However, due to their limited field weakening capability, these motors are difficult to expend constant power speed region, as the presence of the fixed PM magnetic field.

The speed range may be extended three to four times over the base speed. To realize the wide speed ranges in these motors, an additional dc field excitation coil (FEC) winding is introduced, in such a way that the air-gap field provided by PMs can be weakened during a high-speed constant-power operation by controlling the direction and magnitude of the dc field current which are also called PM hybrid motors. However, at a very high-speed range, the efficiency may drop because of increase in iron loss and also there is a risk of PM demagnetization [7-9].

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 utilize 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. In other literatures, the PMSM is also particularly suited for the wheel direct-drive motor applications.

2.3 Classifications of Flux Switching Machine (FSM)

Generally, the FSMs can be categorized into three groups that are permanent magnet flux switching machine (PM), field excitation flux switching machine (FE), and hybrid excitation flux switching machine (HE). Both PM and FE has only PM 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.

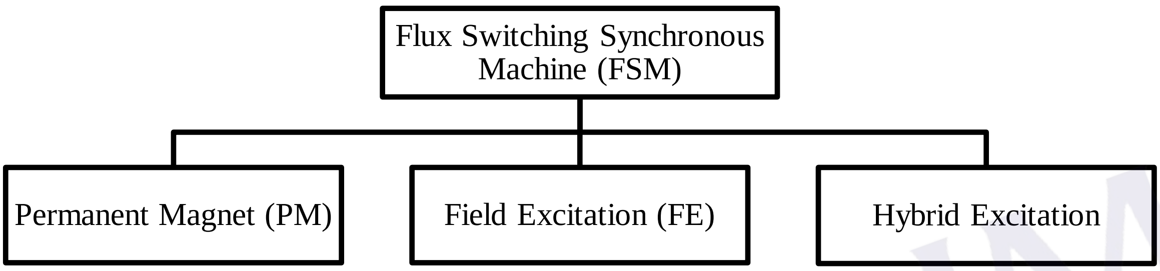


Figure 2.2: General classification of FSM

2.3.1 Permanent Magnet Flux Switching Machine (PMFSM)

PM machine based on the principle of flux switching have been studied for several decades. Generally, such machines 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), i.e., the flux linkage switches polarity as the salient pole rotor rotates.

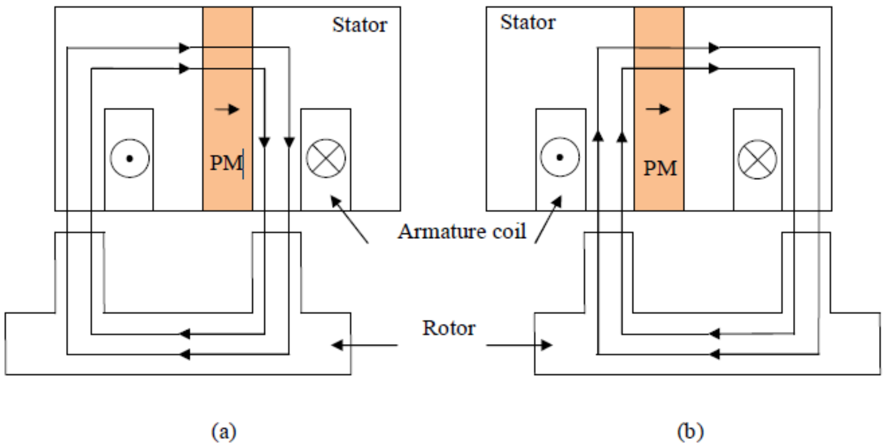


Figure 2.3: Principle operation of PMFSM

2.3.2 Field Excitation Flux Switching Synchronous Machine (FEFSM)

FEFSM is a form of salient-rotor reluctance machine with a novel topology, combining the principles of the inductor generator and the SRMs [16-18]. 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 [19-21]. 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. Fig. 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 [22]-[23].

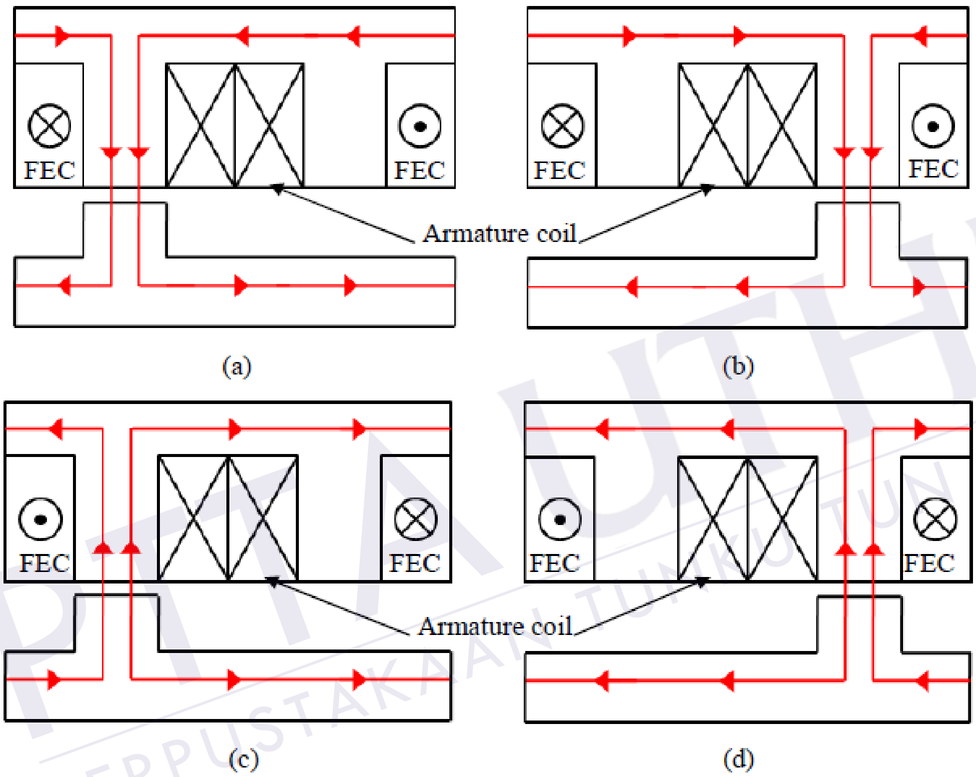


Figure 2.4: Principle operation of FEFSM (a) θ*e*=0° and (b) θ*e*=180° flux moves from stator to rotor (c) θ*e*=0° and (d) θ*e*=180° flux moves from rotor to stator

2.3.3Hybrid Excitation Flux Switching Synchronous Machine (HEFSM)

Hybrid excitation flux switching machines (HEFSM) are those which utilize primary excitation by PMs as well as DC FEC as a secondary source. Conventionally, PMFSM 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 machines and DC FEC synchronous machines are combined. As such HEFSM 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 [24-26].

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 II.

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

Table 2: Advantages and disadvantages of FSM

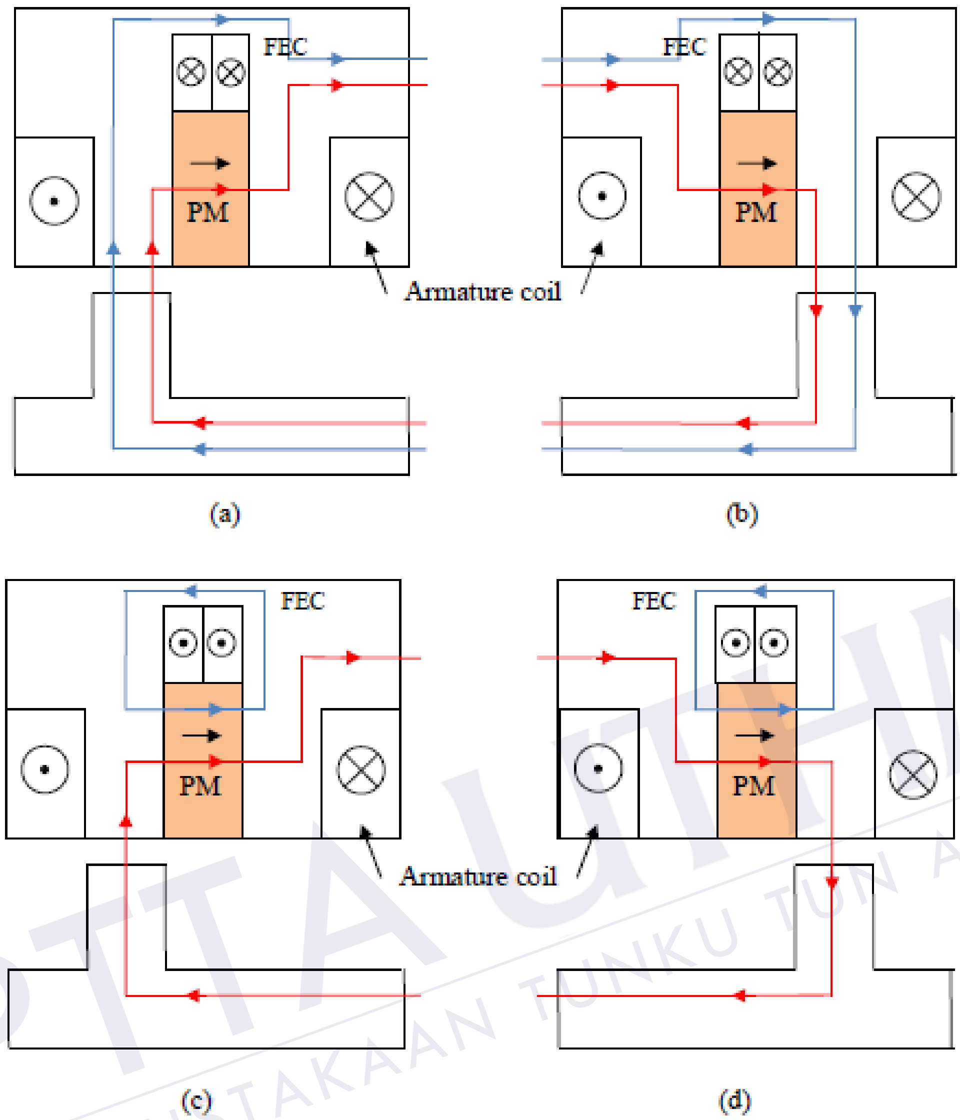


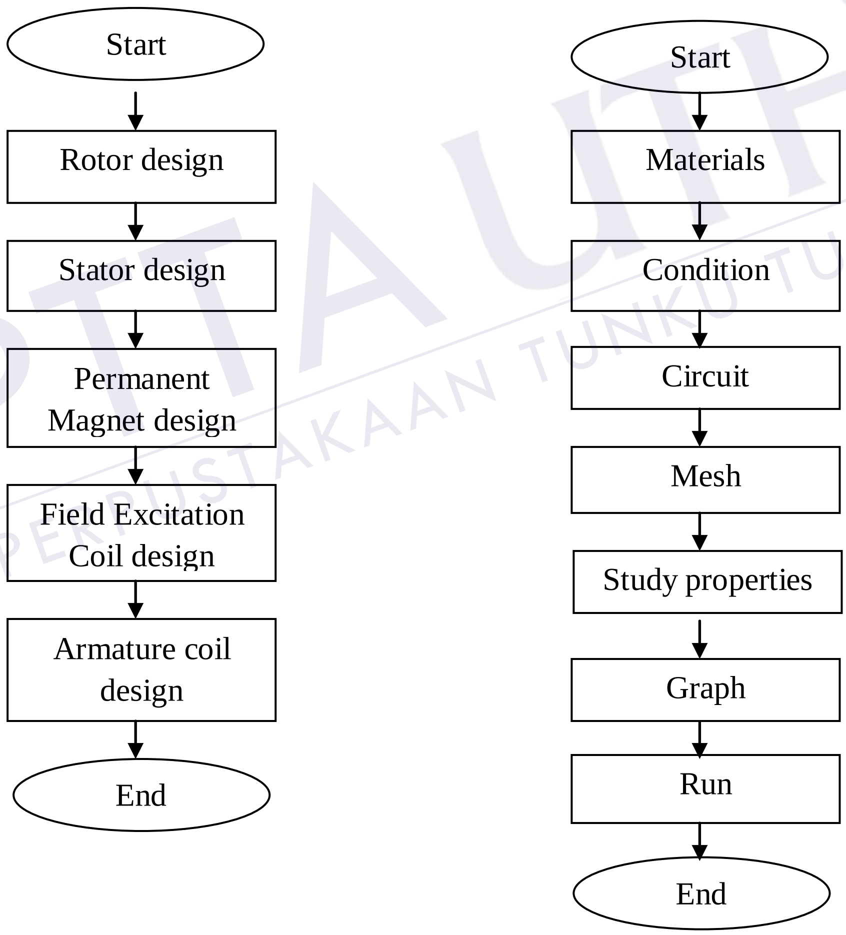
Figure 2.5: The operating principle of the proposed HEFSM (a) θe=0° - more excitation (b) θe=180° - more excitation (c) θe=0° - less excitation (d) θe=180° - less excitation.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology of this research is by using JMAG-Designer version 11 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 3.1 and Figure 3.2 respectively.



(a)Flow chart of geometry editor (b) Flow chart of JMAG-Designer

Figure 3.1: Work flow of project implementation

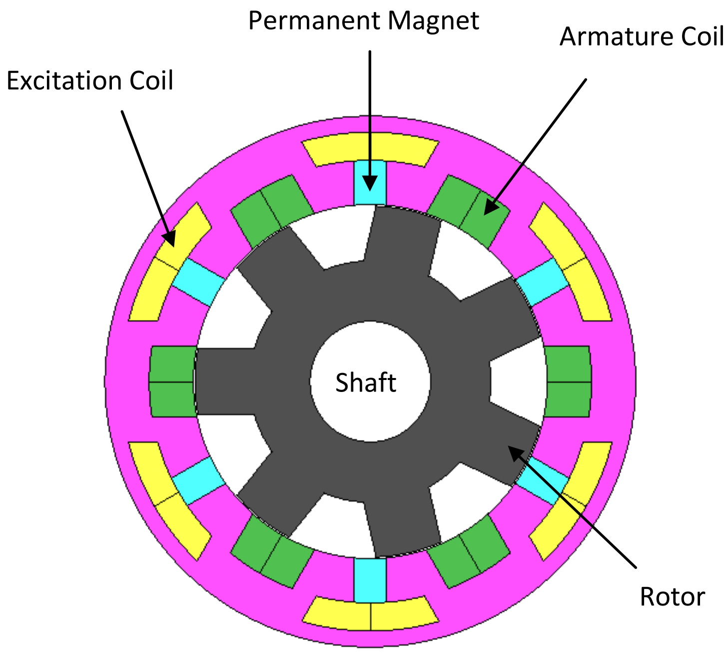


Figure 3.2: Design of 6S-7P HEFSM

Design parameters of 6Slot-7Poles HEFSSM for HEV applications are shown in Table III below.

Table 3: Design parameters of design 6S-7P HEFSM

1.	Rotor radius(mm)	87.2
2.	PM height(mm)	23.0
3.	FEC width(mm)	24.0
4.	FEC height(mm)	6.2
5.	AC width(mm)	7.5
6.	AC height(mm)	27.0
7.	Stator outer diameter(mm)	264
8.	Shaft radius(mm)	30
9.	Air gap length(mm)	0.8

3.2 Geometry Editor

Geometry editor is used to design the rotor, stator, PM, FEC and AC parts. Figure 3.3 shows the toolbar which used in designing the motor parts.

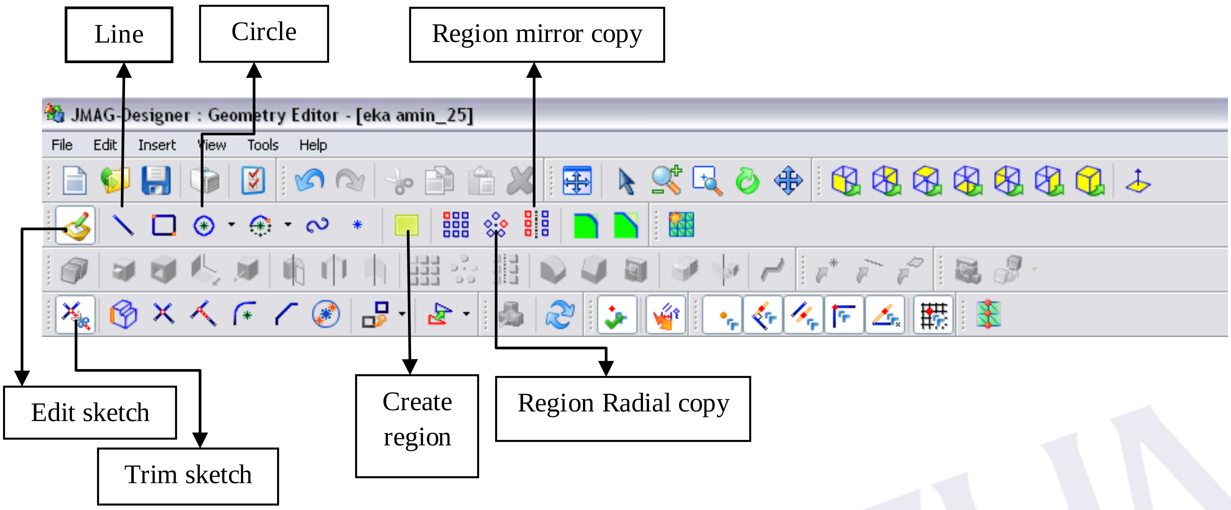


Figure 3.3: Shortcut menu/Toolbar of Geometry Editor

3.2.1 Rotor design

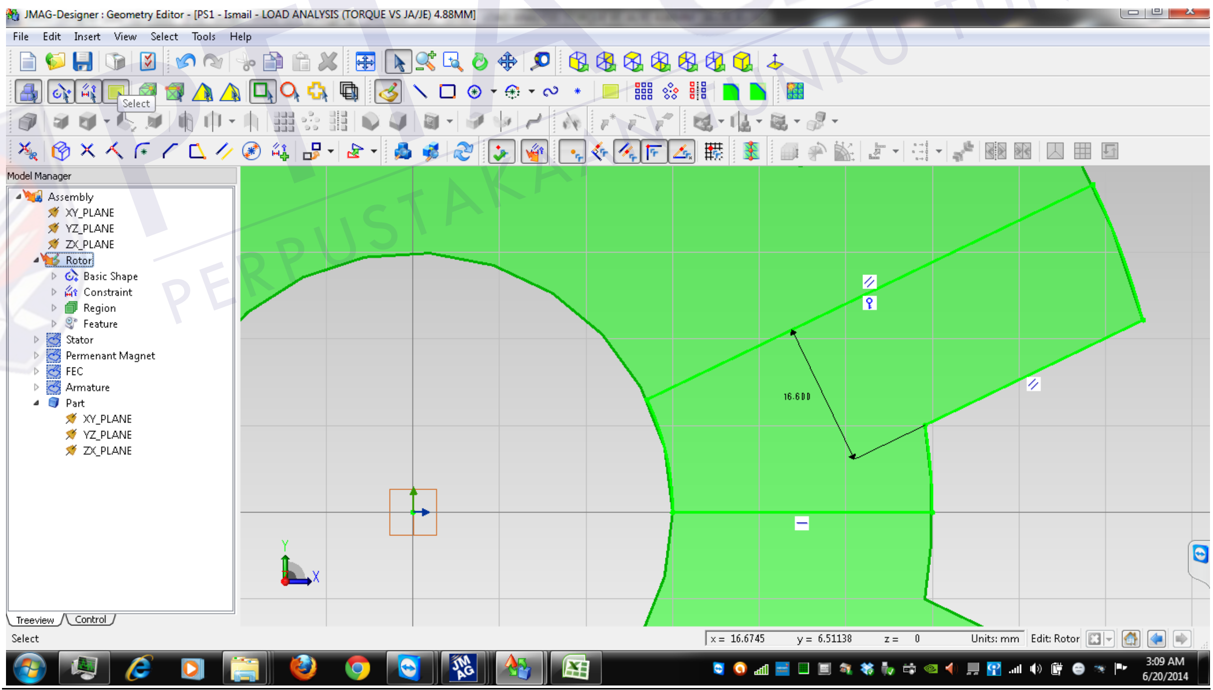


Figure 3.4: Rotor Sketch

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