PERFORMANCE INVESTIGATION OF
6S-4P, 6S-5P, 6S-7P AND 6S-8P
HEFSM

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ABSTRACT

Hybrid Electric Vehicles (HEV) was become prevalent and widely used since last few years. Within the HEV, the best candidate for electric-propulsion system is Interior Permanent Magnet Synchronous Motor (IPMSM). Despite of fine operation, constant state of flux and high cost due to limited and expensive rare-earth magnet price, alternative to the IPMSM was at desirable state.

HEFSM was identified as new candidate of electric-propulsion system for HEV. HEFSM utilized both Permanent Magnet (PM) as primary excitation and Field Excitation Coil (FEC) as secondary excitation to produce flux. As such variable and high flux control capabilities make HEFSM more attractive. Thus HEFSM have the potential in improving torque and power density. On top of that, both PM and FEC was located at stator which make HEFSM become more robust and easy to design compared to the IPMSM.

In this study, different model using 6 slot and various pole of HEFSM were designed using Geometry Editor in JMAG Designer Version 13. Simulation on the each model were completed. The measurement of HEFSM initial performance is critical to understand the condition and reaction of each model. Thus analysis on the performance of each model based 2D finite element analysis (FEA) were performed at no-load and at load condition. Among performance analysis for HEFSM at no-load are UVW coil test, flux distribution and cogging torque.

At load condition, each model of HEFSM were introduced by varied armature current densities (Ja) and FEC current densities (Je) from 0 to 30 A/mm^2. Hence investigation on performance such as Torque versus various current density and Torque versus Speed were executed. It is very vital to understand the performance of HEFSM at no load and at load are varied by adding 10% of FEC circumference of cross section area. On top of that, comparison on the performance between new designed model and previous model was also conducted.

ABSTRAK

Kenderaan Electrik Hibrid (*Hybrid Electric Vehicles (HEV)*) telah digunakan oleh ramai secara meluas semejak beberapa tahun lepas. Untuk "HEV", calon yang terbaik untuk sistem motor elektrik ialah "*Interior Permanent Magnet Synchronous Motor (IPMSM)*". Walaupun operasi sistem berjalan dengan lancar, fluk yang tetap dan kos yang tinggi disebabkan oleh magnet nadir bumi yang terhad dan mahal, alternatif kepada "IPMSM" adalah pada keadaan diperlukan.

"Hybrid Excitation Flux Switching Machines (HEFSM)" telah dikenalpasti sebagai calon baru kepada sistem motor elektrik untuk "HEV". "HEFSM" menggunakan kedua-dua Magnet Kekal *("Permanent magnet (PM)")* sebagai pengujaan pertama dan Bidang Pengujaan Gegelung *("Field Excitation Coil (FEC)")* sebagai pengujaan kedua untuk menghasilkan fluks. Dengan keupayaan fluks yang boleh berubah serta tinggi telah membuat *"HEFSM"* nampak lebih menarik. Oleh itu HEFSM mempunyai potensi di dalam meningkatkan daya kilas dan kuasa kepadatan. Selain itu, kedua-dua "PM" dan *"FEC"* terletak di statur yang membuat *"HEFSM"* menjadi lebih mantap dan mudah untuk direka bentuk berbanding dengan *"IPMSM"*.

Dalam kajian ini, model *"HEFSM"* yang berbeza direka menggunakna 6 slot dan pelbagai "*pole*" menggunakan Geometri Editor versi JMAG Designer 13. Simulasi kepada setiap model telah dilaksanakan. Pengukuran prestasi awal *"HEFSM"* adalah kritikal untuk memahami keadaan dan tindak balas bagi setiap model. Oleh itu analisis mengenai prestasi setiap model berdasarkan "*2D finite element analysis (FEA)*" dijalankan dengan beban dan tanpa beban. Antara analisis prestasi untuk *"HEFSM"* tanpa beban adalah ujian gegelung UVW, peredaran fluks dan "cogging" tork.

Dalam keadan dengan beban, setiap model "*HEFSM*" telah diperkenalkan dengan pelbagai "armature current densities (Ja)" and "*FEC current densities (Je)*" dari 0 to 30 A/mm^2. Oleh itu siasatan terhadap prestasi seperti tork berbanding pelbagai ketumpatan arus dan tork berbanding kelajuan telah dilaksanakan. Ia adalah sangat penting untuk memahami prestasi "HEFSM" tanpa beban dan pada beban yang diubah dengan menambah 10% "*FEC*" pada keratan rentas. Selain itu, perbandingan prestasi antara model yang direka bentuk dengan model sebelumnya juga dijalankan.

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CHAPTER 1

INTRODUCTION

1.1 Background of study

The first fuel-electric hybrid car was introduced to the world in 1901 by Porsche. It was named Lohner-Porsche Mixte Hybrid. During that year, Hybrid Electric Vehicles (HEV) does not become prevalent and widely available due to the low cost of fuel and also higher electric car price compared to the conventional. With the increase of fuel price and also awareness on the greenhouse effect, automobile maker perceived the HEV demand will increase in the future. As of FY2014, 1.35 million hybrid cars were sold worldwide in last two years, and then more research and design were conducted on electric driver or motor in order to produce a more cost efficient and high performance electric motor and HEV.

One of the successful electric motors designed for HEV is interior permanent magnet synchronous motors (IPMSMs). IPMSM is leading due to smaller size, lighter weight and higher efficiency. Moreover it can operate at higher speed than 12000 rpm. But the drawback are: it is difficult to design [1] and reducing maximum torque due to increase in flux leakage [2]. Alternative to IPMSM is Flux Switching Machine (FSM).

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Machines (HEFSM) is one of the possible alternative that is suitable for high speed operation at high torque and power density. HEFSM utilized primary excitation by permanent magnets (PM) as well as DC field excitation coil (FEC) as a secondary source in electric driver [3]. Meanwhile PMFSM only utilized PM as its main flux source and it can operate beyond base speed in the flux weakening region by means of controlling the armature winding current. Still, the disadvantage of PMFSM is it has relatively poor flux weakening performance but, by applying negative d-axis current, the PM Field can be counteracted. Consequently, reducing the result in copper loss thus efficiency and power capability are reduced. Moreover, it will result in a possible irreversible demagnetization of the PMs. The third category of FSM is FEFSM and it only utilize FEC as main flux source. FEFSM has very simple configuration, low cost and reduce the coil end problem. However, the disadvantages of FEFSM are that the FEC flux can't be controlled and high iron losses, thus reducing the efficiency and power capability.

Therefore, HEFSM is one of the alternative options 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 [4] [5] [6].

1.2 Problem Statement

Hybrid electric vehicles (HEVs) is a combination of an internal combustion engine (ICE) and one or more electric motors. HEV is widely considered as the most promising solution for clean vehicles. IPMSM is currently successfully built for the most famous HEV. However due to several factors shown below, alternative to IPMSM is desirable.

a) Limited resource and expensive rare-earth magnet material
b) Limited torque at high speed capabilities
c) The design tends to be difficult due to all permanent magnets (PMs) are built inside the rotor core. IPMSM has non-robust rotor

d) Low cooling system for heat dissipation due to PM in the rotor core

In fact, the automobile makers are seeking for the most suitable electric-propulsion system for HEVs and even for EVs. The choice of electric-propulsion systems for HEV depends on three factors; which are driver's expectation, vehicle design constraints, and energy source. With these considerations, it is understood that the specific motor operating points are difficult to define [3]. In recent work, a new candidate of Hybrid Excitation Flux Switching Motor (HEFSM) with rugged rotor structure is studied for high-speed operation and ability to keep high torque and power density. In earlier study, HEFSM with various combinations of stator slot and rotor pole for HEV was designed, developed and tested for high speed application. Various combinations of stator slot and rotor pole or model will give different performance results. In this study, a 6S-4P, 6S-5P, 6S-7P and 6S-8P were designed and performance of each model was considered.

From previous design, the 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 the advantage of less cogging torque and almost no back-emf at open-circuit condition [7] [8].

1.3 Objectives of the study

The objectives of this research are:

a. To design a 6S-4P, 6S-5P, 6S-7P and, 6S-8P HEFSM.

b. To comprehend on no-load performance of 6S-4P, 6S-5P, 6S-7P and, 6S-8P HEFSM by analyze the profile of zero rotor position, flux strengthening, and cogging torque based on 2D finite element analysis (FEA) and to investigate the load performance of 6S-4P, 6S-5P, 6S-7P and, 6S-8P HEFSM by introduced varied armature current densities (Ja) and FEC current densities (Je) from 0 to 30 A/mm^2. The initial performances of the selected HEFSM are evaluated based on 2D-FEA and compared with HEFSM from previous study.

1.4 Scopes of study

The scopes of study are focused on

a. To comprehend on selected model of HEFSM and technique to design using Geometry Editor in JMAG Designer Version 13 released by Japanese Research Institute (JRI).

b. To design for the selected model of HEFSM and run the simulation. To understand the tabulated data and perform the analysis.

c. To observe the performance on selected model of HEFSM at no-load and on load using 2D-FEA. To relate the initial load performance of selected model of HEFSM to the previous study in [3].

For the design on selected model of HEFSM, the design restrictions and target specifications of the proposed machine are listed in Table I. This table includes the current 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].

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 with residual flux density and coercive force at 20°C are 1.2T and 932kA/m, respectively while the electrical steel 35H210 is used for rotor and stator body [3].

SPECIFICATION	Value
Max. DC-bus voltage inverter (V)	650
Max. inverter current (Arms)	360
Max. current density in armature winding, Ja (Arms/mm2)	30
Max. current density in excitation winding, Je (A/mm2)	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

Table 1.1 HEFSM Design Restrictions and Specifications Items

1.5 Thesis Structure

This project thesis is organized as follows:-

Chapter 1 covers the background of the study, problem statement, objectives of the project, project scope and thesis structure.

Chapter 2 presents the literature review on the FSM family. Starting with HEFSM, followed by PEFSM and then FEFSM.

Chapter 3 elaborates on the methodology of works; starting with the design of a rotor, stator, PM and FEC using Geometry Editor for each topologies of HEFSM. The next step after design completion is to choose material, perform condition setting, construct AC and DC circuit and finally run the analysis in JMAG Designer. Various data such as magnetic flux, flux level at different degree and cogging torque are tabulated from the test. From the data, various graph can be established to evaluate the performance of selected HEFSM. The relevant calculation such as number of turn, rotor width and related information to the HEFSM are also clarified in this chapter.

Chapter 4 reports and discuss on the result from the simulation. The performance of the HEFSM are compared between them to identify the best model for the selected design specification.

Chapter 5 will go through about conclusion and recommendation for future study. Reference cited and supporting appendices are given at the end of this report while the documentation CD is also available and attached on the back cover of this project report for future reference.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are three types of vehicles which powered by electricity. It's an electric vehicles (EV), hybrid electric vehicles (HEV), and plug-in-electric vehicles (PHEV). These vehicles not only reduce fuel usage than conventional vehicles but also alternatives for reducing air pollution and greenhouse gas emissions.

Electric Vehicles (EVs) are enforced by a battery-powered motor, and the battery is charged by plugging the vehicle into the electric grid either at home or at a public charging station. EVs do not have an internal combustion engine (ICE) and therefore no fuel were used. Hybrid Electric Vehicles (HEVs) are powered by fuel as well as electric power stored in a battery. The battery is charged through regenerative braking and the internal combustion engine. In other words, the battery captures energy normally lost during breaking by using the electric motor as a generator. Unlike EVs and PHEVs, HEVs are not plugged into charger. Because HEVs use both electricity and fuel, this vehicle is a good option for driving long distances. Plug-in Hybrid Electric Vehicles (PHEVs) are powered by conventional or alternative fuels as well as electric power stored in a battery. The battery can be charged by plugging it into an outside power source, by the internal combustion engine, or by regenerative breaking. Unlike HEVs, which still depend on petroleum, it is possible for PHEVs to run on only electricity when fully charged. Because PHEVs can run off gas or electricity, they are a good option for driving long distances if availability of charging station are uncertain.

With the growing attention to this new generation of vehicles, often called electric drive vehicles, more effort is demanded to develop high efficiency, reliability and economical drives for electric propulsion. Therefore, the selection of electric motor become a very important step by automobile maker.

HEV have been in production for several years and automobile maker still seeking for the most suitable electric propulsion system for HEV. There are several factors to consider the appropriate electric propulsion system such as driver's expectation, vehicle design constraints and energy source. One of successfully electric motor designed for HEV is interior permanent magnet synchronous motors (IPMSMs).

2.2 Hybrid Electric Vehicles (HEVs)

Hybrid electric vehicles (HEVs) using combination of an internal combustion engine (ICE) and one or more electric motors are widely considered as the most promising solution for clean vehicles. One example of successfully developed electric machines for HEVs is interior permanent magnet synchronous motor (IPMSM), selected due to its smaller size and lighter weight providing with design freedom of the vehicles and its higher efficiency contributing to less fuel consumption. However, IPMSM design tends to be difficult due to all permanent magnets (PMs) are built in the rotor core. The mechanical strength relies mainly on thickness and number of bridges around PM but high number of bridges reduces the maximum torque due to increases in flux leakage. Therefore, a new candidate of hybrid excitation flux switching motor (HEFSM) with rugged rotor structure suitable for high-speed operation and with the ability to keep high torque and power density. 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:

1. High instant power and high power density
2. High torque at low speed for starting and climbing, as well as high power at high speed for cruising
3. Very wide speed range, including constant-torque and constant-power regions
4. Fast torque response
5. High efficiency over the wide speed and torque ranges
6. High efficiency for regenerative braking
7. High reliability and robustness for various vehicle operating conditions
8. Reasonable cost

2.3 Flux switching machine

Flux switching machine (FSM) has become one of popular research topic due to their advantages such as higher torque density and efficiency [9]. FSM is classified into 3 types. The first type is permanent magnet flux switching machine (PMFSM). The second type is field excitation flux switching machine (FEFSM) and the last type is hybrid excitation flux switching machine. PMFSM employ permanent magnet as it main flux source. Whereas FEFSM uses field excitation coil (FEC) as its main flux sources. For HEFSM, it combines both PM and FEC as its main flux sources [1]. The types of FSM can be summarized into figure below:

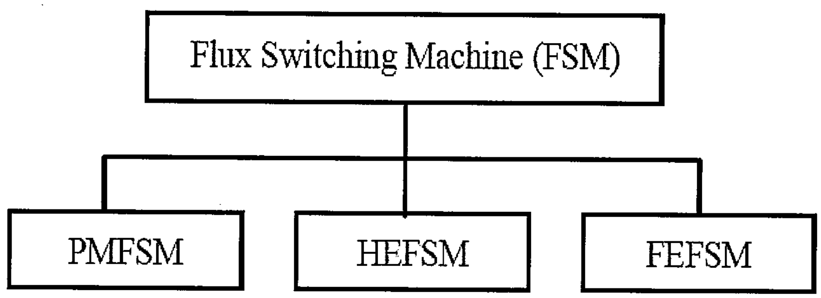


Figure 2.1 Classification of Flux Switching Machines (FSM)

The advantages and disadvantages of FSM discussed in this chapter are listed in Table 2.1.

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

Table 2.1 Advantages and Disadvantages of FSM.

2.3.1 Permanent Magnet Flux switching Machine (PMFSM)

Permanent magnet flux switching machine has become a popular research topic recently due to high power density and robust motor structure [10]. The PMFSM is more advantage than conventional PM machine because of these following factors. The active parts in the stator such as armature coil and permanent magnet have better cooling ability. Next, it is more suitable for high speed applications [10][11][12]. Moreover it is suitable to be used in harsh operating environment such as space, automotive and wind energy applications [13]. Generally, PMFSM have the distinct characteristic. It has salient pole rotor which is similar to that of SRMs. By moving the magnet to stator, the slot area is reduced and heat dissipation from stator can be control more easily.

The general operation principle of the PMFSM is illustrated in Fig. 2.3. At the position in Fig. 2.2 (a), the PM flux which is linked in the coil goes out of the coil and into the rotor tooth. When the rotor moves forward to the direction in Fig. 2.2 (b), the PM flux goes out of the rotor tooth and into the stator tooth, keeping the same amount of flux-linkage whilst reversing the polarity, i.e., realizing the "flux-switching". Consequently, as the rotor moves, the flux-linkage in the windings will change periodically, and back-EMF will be induced. Both the PM flux-linkage and back-EMF can be sinusoidal versus the rotor position as long as the machine is properly designed, thus it can be driven in the blushless ac (BLAC) mode [14].

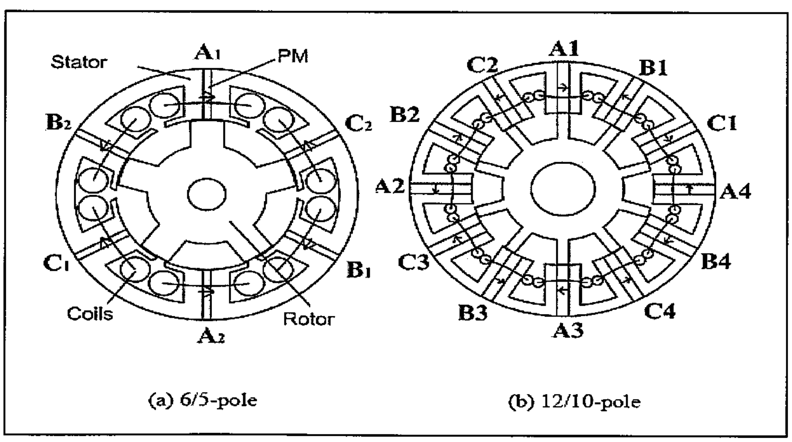


Figure 2.2 Cross-sections of 3 phase PMFSMs

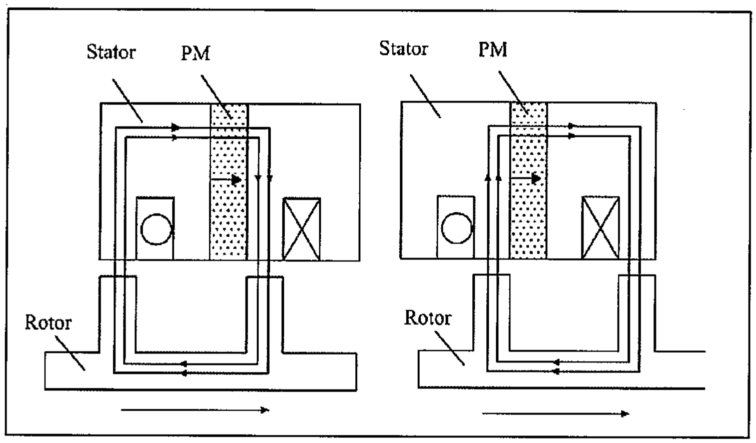


Figure 2.3 Operation Principle of PMFSM

2.3.2 Field Excitation Flux Switching Synchronous Machine (FEFSM)

Flux switching motor concept is founded and published in mid 1950s. Synonym to the name, flux switching is the main principle used in FEFSM motor operation. In the motor operation, the stator tooth flux switches polarity following the motion of a salient pole rotor, thus "flux switching" is lay claim to [15][16]. The advantage of this machine is robust rotor structure that appropriate for high speed applications. In addition, the FEC can be used to manage the generated flux with variable capabilities. In the FEFSM, the probable number of rotor pole and stator slot is defined as in (1),

$$N_r = N_s(1 \pm \frac{k}{2q}) \qquad (2.1)$$

Where N_r is the rotor poles number, N_s is the number of stator slots, q is the number of phases and the natural number is defined as k. For the proposed motor, q = 3, N_s =12 and N_r is even numbers that varies from 10 to 22. In this proposed motor, the motor rotation through $1/N_r$ of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of voltage induced in the armature coil is N_r times the rotational frequency of mechanical.

In general, the rotation frequency of mechanical, fm and the frequency of electrical, fe for the proposed motor can be articulated as (2),

$$f_e = N_r f_m \tag{2.2}$$

Where f_e, N_r and f_m is the frequency of electrical, number of rotor poles and mechanical rotation frequency, respectively. The operating principle of the FEFSM is illustrated in Fig. 2.4 (a) and (b) show the direction of the FEC fluxes into the rotor while Fig. 2.4 (c) and (d) illustrate the direction of FEC fluxes into the stator which produces a complete one cycle flux. The stator flux switches between the alternate stator teeth because of the each reversal of armature current shown by the transition between Fig. 2.4 (a) and (b)[15].

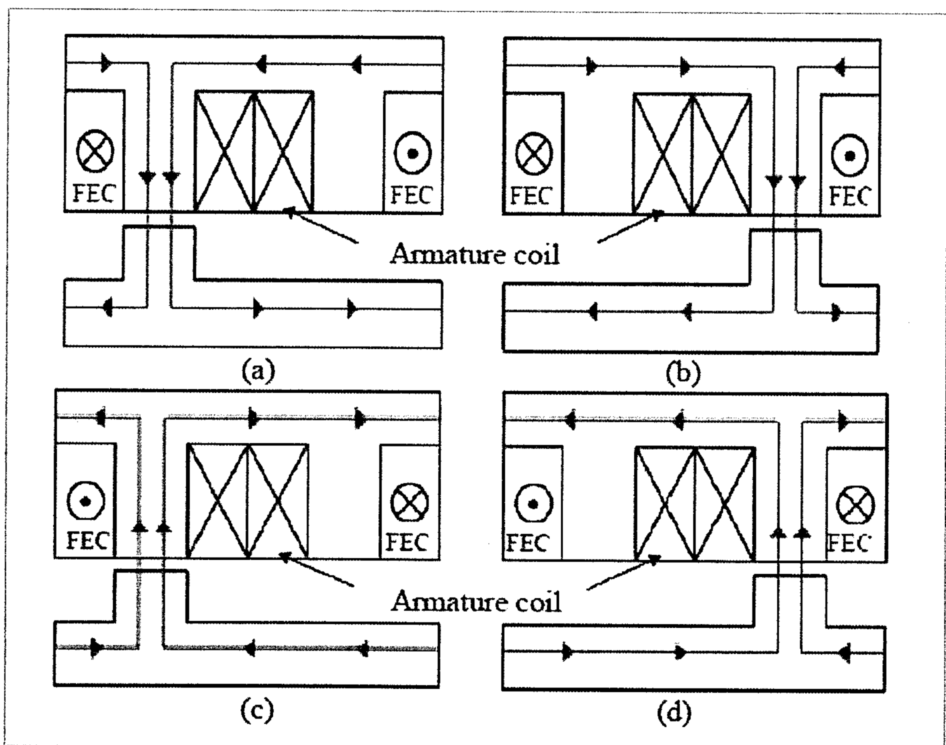


Figure 2.4 Principle Operation of FEFSM (a) θ*e* =0° and (b) θ*e* = 180° flux moves from stator to rotor (c) θ*e* = 0° and (d) θ*e* = 180° flux moves from rotor to stator.

2.3.3 Hybrid Excitation flux Switching Synchronous Machine (HEFSM)

The flux source of the HEFSM is coming from two sources which are PM and DC field excitation coil (FEC). All the active parts are located on the stator with the armature and PM (DC field winding) placed in alternate stator teeth. The advantage of this machine is its robust rotor structure that makes it suitable for high speed applications. In addition, the FEC can be used to control the generated flux with variable capabilities. The possible number of rotor poles and stator slots is defined by equation 2.1.

$$N_r = N_s(1 \pm \frac{k}{2q}) \tag{2.1}$$

Where Nr is the number of rotor poles, Ns is the number of stator slots, k is an integer, and q is the number of phases. For the motor, q = 3, Ns =6 and Nr = 6. In this motor, the motor rotation through 1/6 of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is six times that of the mechanical rotational frequency. In general, the relation between the mechanical rotation frequency, fm and the electrical frequency, fe for the machine can be expressed as,

$$f_e = N_r f_m \tag{2.2}$$

Where fe is the electrical frequency, fm is the mechanical rotation frequency and Nr is the number of rotor poles. The operating principle of the proposed inner-rotor HEFSM is illustrated in Figure 2.6. The stator is presented, where the PM, FEC, and armature coil are located. The PM and FEC are placed between two stator poles to generate excitation fluxes, from which the term of "hybrid excitation flux" originated. The red line indicator shows the flux from PM while the blue indicator shows flux from FEC. The flux generated by PM and FEC are flowing in the same polarity. Both fluxes are combined and moves from stator to rotor and return back through the next rotor pole to the next stator teeth to complete one flux cycle. The combinations of both fluxes are called hybrid excitation flux. Due to the combination of the two fluxes, hybrid excitation flux will produced higher torque. When the rotor starts to rotate and moves to the right, the rotor pole will be allocated to the next stator tooth. This will cause the magnitude and polarities of the flux linkage change their direction. Therefore the magnetic flux generated by FEC and PM is only changes their direction toward the armature coil slot and not rotate as movement of the rotor. Figure 2.6 (c) and (d) shows the FEC setting. As previously described, the red line indicator shows the flux from PM while the blue indicator shows flux from FEC. It can be seen that, only PM flux contribute to flux flows from the stator into the rotor and from the rotor into the stator. The FEC flux is only circulates on its particular winding. This condition establishes less excitation flux as compared to hybrid flux excitation and hence generates less torque.

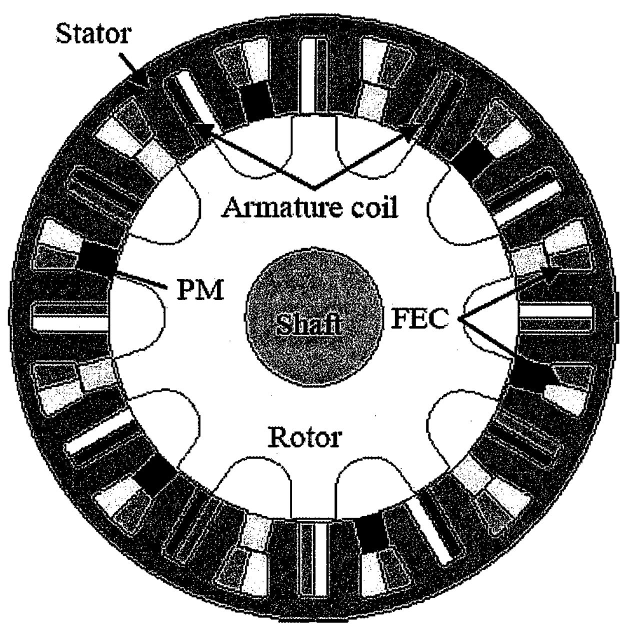


Figure 2.5 Cross sectional view of inner-rotor HEFSM

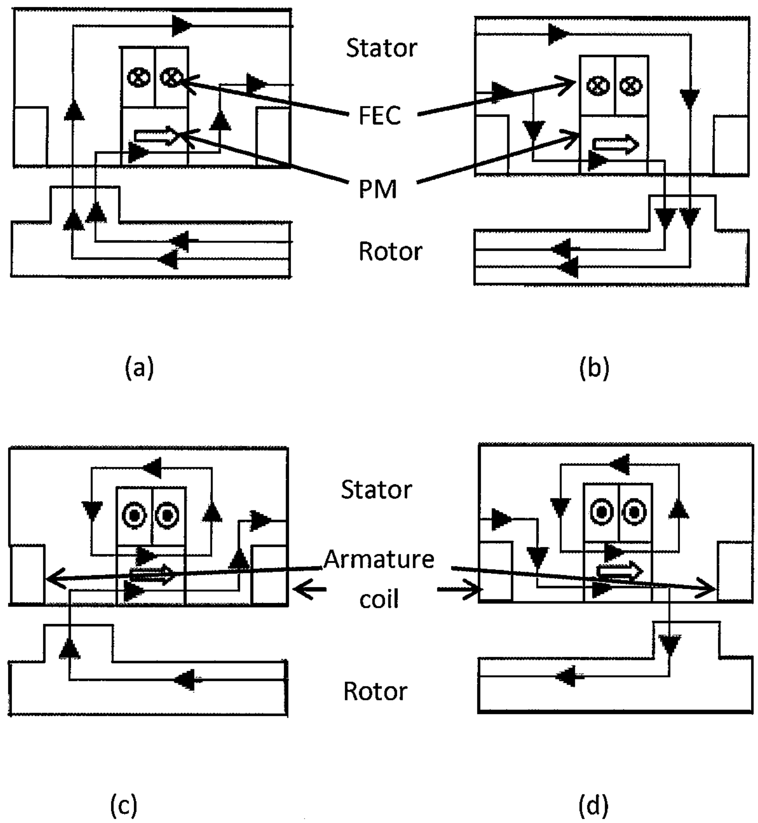


Figure 2.6 Principle operation of HEFSM (a) θe = 0° and (b) θe = 180° flux moves from stator to rotor, (c) θe = 0° (b) θe = 180° flux moves from rotor to stator.

CHAPTER 3

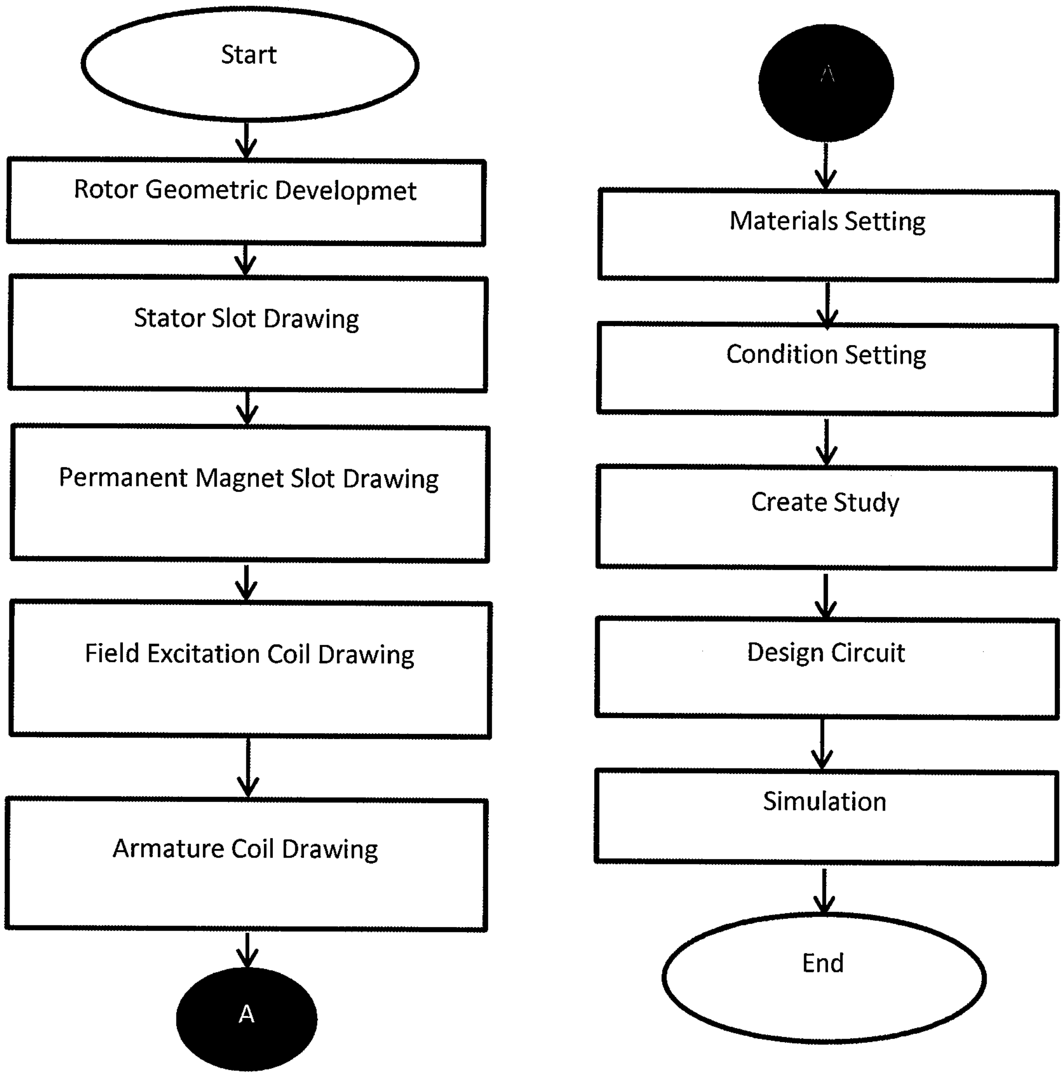
METHODOLOGY

3.1 Introduction

This chapter deliberates on the details framework of the study. This study is divided into three parts. The first part is to design the model of HEFSM. There are 4 models namely 6S-4P, 6S-5P, 6S-7P and 6S-8P. In this design, most of specification, restriction and requirement of the four HEFSM models were based on previously studied HEFSM models [3]. However 10% of FEC circumference of cross section are added to the new design. Original area are 392.77mm^2 meanwhile new design will having 432.89mm^2. In this study, JMAG-Designer version 13 software was used to design the motor. JMAG is 2D–FEA simulation software for the development and design of electromechanical machine. JMAG was originally release in 1983 as a tool to support design for devices such as motors, actuators, circuit component, and antennas. After completion of designed HEFSM, material was chose, condition was setting and AC & DC was setup to run the simulation. Second part is to perform no load analysis and last part is to perform on Load analysis

3.2 Design of 6S-4P, 6S-5P, 6S-7P and 6S-8P HEFSM.

The design of the HEFSM was divide into two parts which is by using Geometry Editor and it was continued by using JMAG-Designer. The work flow of the geometry editor and JMAG-Designer were illustrated in Figure 3.1.



(a) Geometry Editor Flow Chart (b) JMAG-Designer Flow Chart

Figure 3.1 Design of 6S-4P, 6S-5P, 6S-7P and 6S-8P HEFSM Flow Chart.

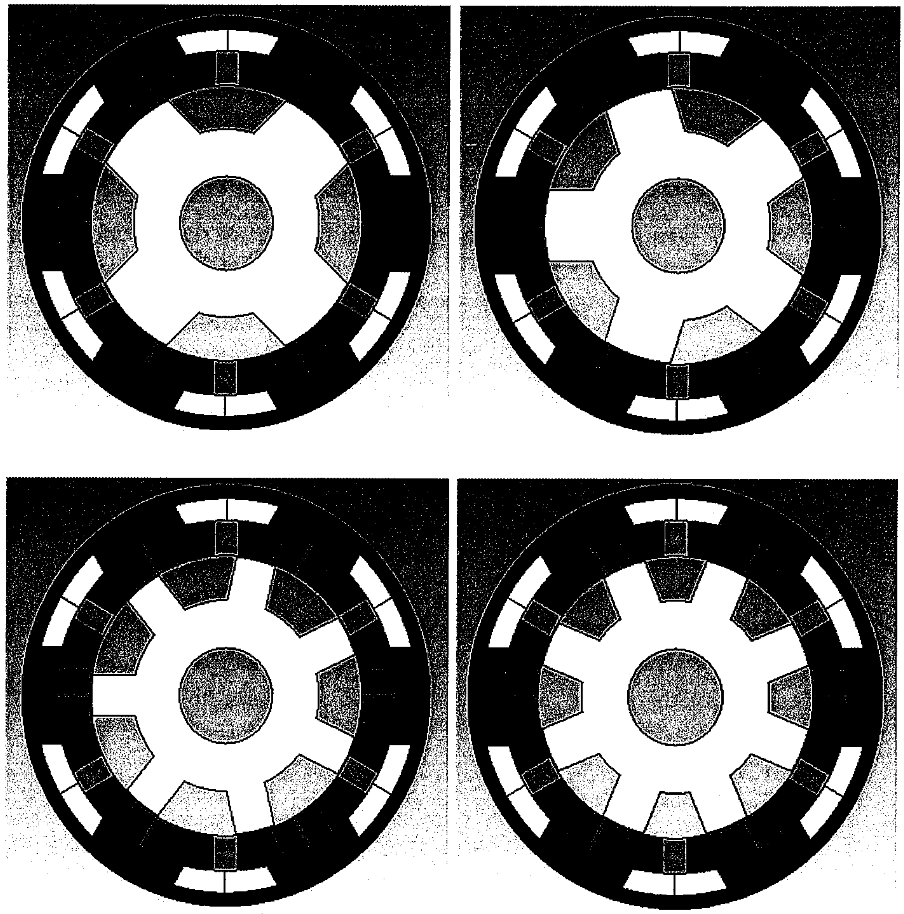


Figure 3.2 Design of 6S-4P, 6S-5P, 6S-7P and 6S-8P HEFSM respectively.

Design parameters of 6S-4P, 6S-5P, 6S-7P and 6S-8P HEFSM for HEV applications were shown in Table 3.1 below.

Rotor radius(mm)	87.2
PM height(mm)	22
FEC height(mm)	14
AC width(mm)	17.752
AC height(mm)	22
Stator outer diameter(mm)	264
Shaft radius(mm)	30
Air gap length(mm)	0.8

Table 3.1 Design parameters of design 6S-7P HEFSM

3.2.1 Geometry Editor

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

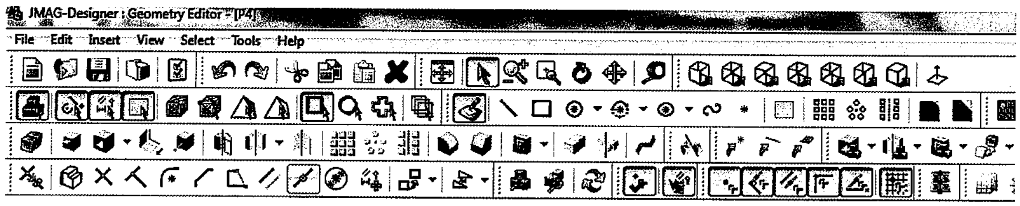


Figure 3.3 Geometry editor

3.2.1.1 Rotor design

For design the rotor, the detailed step as per below:

(i) Click the [ ]Edit sketch icon to start the design of the motor. Right click of the [2DSketch] icon to rename and properties setting such as color.

(ii) Click [ ] circle icon to draw circle. Create three circles with radius 30, 60, 87.2 respectively

(iii) Click [ ] line icon to draw line. To design 4 poles rotor, Create two sets of lines which 90° to each other. Each set have two parallel lines which the span of between the lines was set to 30.667mm apart. To design 5 poles rotor, the two sets of lines was set to 72° to each other and 25.534 mm apart. To design 7 poles rotor, the two sets of lines was set to 51.42857143° to each other and 17.524 mm apart. To design 8 poles rotor, the two sets of lines was set to 45° to each other and 15.334 mm apart.

(iv) Click [ ] trim icon to trim the design into required shape of rotor pole such as Figure 3.4.

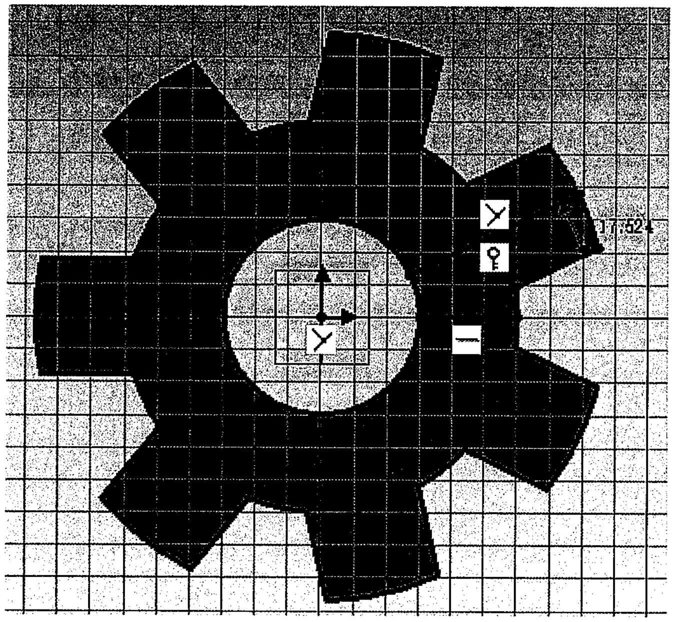


Figure 3.4 Seven poles rotor design

(v) Click [ ] create region icon to create region of the rotor such as in Figure 3.5 for seven poles rotor design.

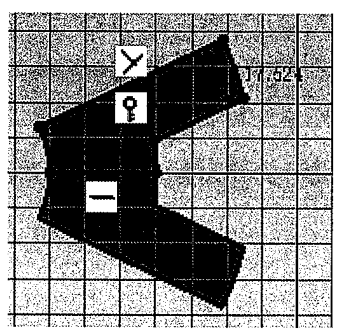


Figure 3.5 S6-P7 rotor region.

(vi) Click [ ] region radial pattern icon and configure the rotor according to Figure 3.6 to complete the seven poles rotor design.

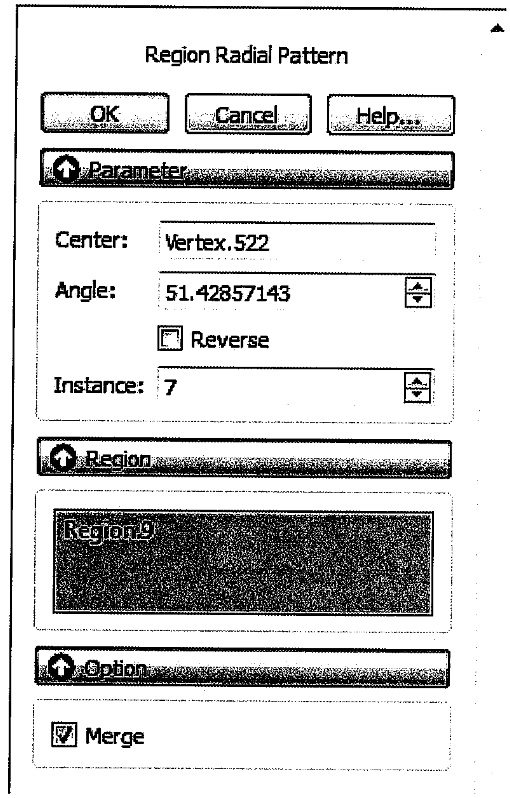


Figure 3.6 Region radial pattern configuration.

3.2.1.2 Stator design

To design the stator, the detail step as per below:

(i) Repeating the rotor design steps accordingly, create a stator region to match Figure 3.7.

(ii) Click [] region mirror copy icon. Select the highlighted line in yellow as reference line in Figure 3.8 and magenta region for its region configuration. A new region as Figure 3.9 is produced.

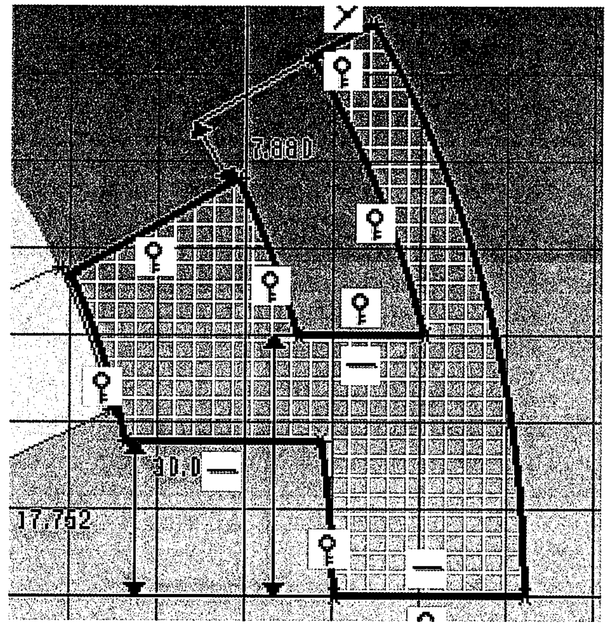


Figure 3.7 Stator design region

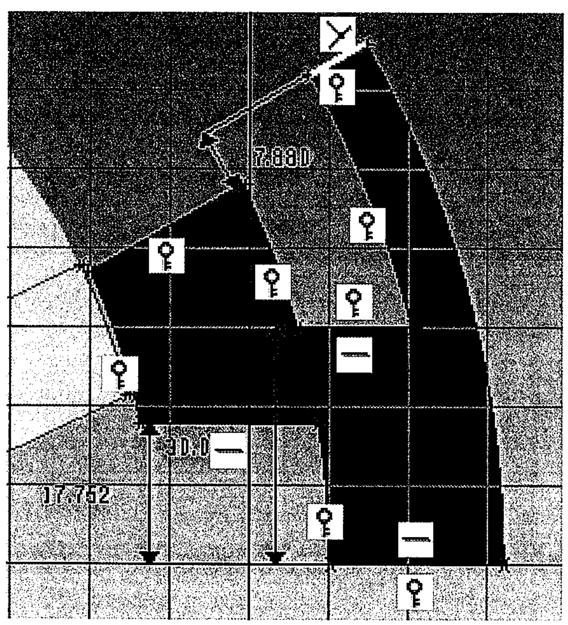


Figure 3.8 Region mirror copy reference line for stator design

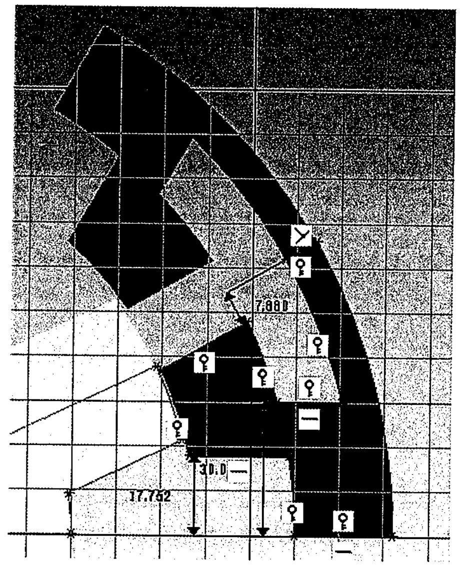


Figure 3.9 A new stator region.

(iii) Click [ ] region radial pattern icon and configure the new stator region according to Figure 3.10 to complete the stator design into Figure 3.11.

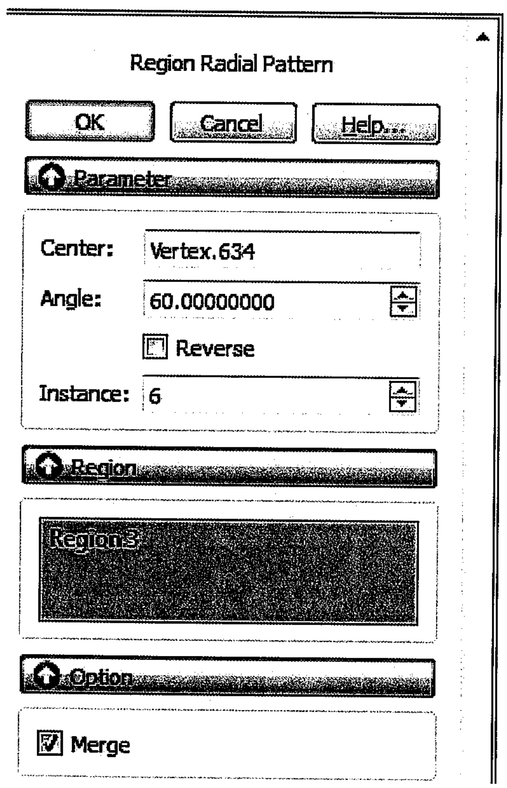


Figure 3.10 Region radial pattern configuration

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