DESIGN STUDY OF THE PROPOSED 12SLOT-14POLE FIELD EXCITATION FLUX SWITCHING MACHINE (FEFSM) FOR HYBRID ELECTRIC VEHICLES

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ABSTRACT

A new structure of field excitation flux switching motor (FEFSM) as an alternative candidate of non-Permanent Magnet (PM) machine for HEV drives is presented in this thesis. Design principles and initial performances of the proposed motor with 12 stator slots and 14 rotor pole are demonstrated. Initially, the coil arrangement tests are examined to validate the operating principle of the motor and to certify the zero rotor position. Furthermore, the profile of flux linkage,cogging torque, torque versus Ja at various Je characteristics and torque versus power characteristics are observed and analyzed based on 2D-finite element analysis (FEA). The improvement design is done by using the “deterministic optimization method” to achieve the restriction and spesification target compared to Interior Permenant Magnet Synchronous Machines (IPMSM) that used in HEV drives. “The results obtained show that proposed 12S-14P FEFSM achieved the target performance for maximum power, maximum torque density, maximum power density and machine weight, while the maximum torque is not achieved as a target. Therefore, by further design modification and optimization it is expected that the low cost motor will successfully achieved the target performances.

ABSTRAK

Satu struktur baru mesin iaitu “*Field Excitation Flux Switching motor”* (FEFSM) dibentangkan di dalam tesis ini sebagai alternatif mesin bukan Magnet Tetap (PM) untuk pemacu “*Hybrid Electric Vehicle”* (HEV). Prinsip reka bentuk dan persembahan awal motor yang dicadangkan dengan 12 slot pemegun dan 14 kutub pemutar ditunjukkan. Pada awalnya, ujian susunan gegelung diperiksa untuk mengesahkan prinsip operasi motor dan kedudukan sifar stator. Tambahan pula, profil rangkaian fluks, cogging tork, ciri-ciri tork berbanding Ja pada pelbagai Je dan ciri-ciri tork berbanding kuasa dipatuhi dan dianalisis berdasarkan analisis unsur terhingga 2D (FEA). Reka bentuk penambahbaikan dilakukan dengan menggunakan “*deterministic optimization method*” untuk mencapai sasaran had dan spesifikasi, yang diukuran berbanding *“Interior Permenant Magnet Synchronous Machine*” (IPMSM) yang digunakan pada pemacu HEV. "Keputusan yang diperolehi menunjukkan bahawa cadangan 12S-14P FEFSM mencapai prestasi sasaran untuk kuasa maksimum, ketumpatan tork maksimum, ketumpatan kuasa maksimum dan berat mesin, manakala tork maksimum tidak dicapai seperti yang disasarkan. Oleh itu, dengan pengubahsuaian reka bentuk dan pengoptimuman lagi adalah dijangka bahawa motor yang berkos rendah akan berjaya mencapai sasaran yang diharapkan.

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PM	Permanent Magnet
FEFSSM	Field Excitation Flux Switching Synchronous Machine
FEFSM	Field Excitation Flux Switching Machine
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
IM	Induction Machines
SRM	Switch Reluctance Machine
PMBL	Permanent Magnet Brushless
DC	Direct Current
IPMSM	Interior Permanent Magnet Synchronous Machines
MRIC	Mineral Resource Information Center
FEC	Field Excitation Coil
AC	Armature Coil
DSPM	Doubly Salient Permanent Magnet
FRM	Flux Reversal Machine
HEFSM	Hybrid Excitation Flux Switching Machine
PMFSM	Permanent Magnet Flux Switching Machine

J_e	Current Density of Excitation Coil
J_a	Current Density of Armature Coil
S_e	Area of Excitation Coil
S_a	Area of Armature Coil

CHAPTER 1

INTRODUCTION

1.1 Research Background

A new structure of field excitation flux switching motor (FEFSM) as an alternative candidate of non-Permanent Magnet (PM) machine for HEV drives is proposed for this project. This project presents the 12Slot-14Pole field-excitation flux switching synchronous machine (FEFSSM) with all active parts i.e. field excitation coil (FEC) and armature coil are located on the stator, applied for hybrid electric vehicles (HEVs). The rotor part consists of single piece iron makes it more robust and becoming more suitable to apply for high speed motor drive system application coupled with reduction gear [**1**]. This project deals with design and improvement of the proposed 12S-14P inner rotor field excitation flux switching motor(FEFSM) for electric vehicle applications. The design restriction and target specifications of the proposed machine for HEV compare with conventional IPMSM.

Hybrid electric vehicles (HEVs), via combination of an internal combustion engine (ICE) and one or more electric machines, are widely measured as the most promising solution for clean vehicles. There are four major types of electric machine that are feasible for HEVs, namely, DC machines, induction machines (IM), switch reluctance machines (SRM), and permanent magnet (PM) brushless (PMBL) machines. DC machines are used to be widely accepted for EVs and HEVs because of their advantage of simple control of the orthogonal disposition of field and armature mmf. However, the principle problem of dc drives, due to their commutators and brushes, makes them less reliable and unsuitable for a maintenance-free operation [**2**] [**3**] [**4**].

In other circumstances, induction machines are a widely accepted brushless drive for the electric propulsion of HEVs, owing to their reliability, ruggedness, low maintenance, low cost, and ability to operate in hostile environments. However, the presence of a breakdown torque limits its extended constant-power operation. At the critical speed, the breakdown torque is reached. Generally, for a conventional IM, the critical speed is around two times the synchronous one. 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, due to the absence of rotor winding and rotor copper losses .

Meanwhile, SRM have been recognized to have a considerable potential for HEVs. They have the definite advantages of simple construction, low cost, and outstanding torque-speed characteristics. Although they possess simplicity in construction, their design and control are difficult and subtle. In addition, they usually exhibit acoustic-noise problems [**5**]. Finally, PMBL machines are becoming more and more attractive and can directly compete with the induction machines for HEVs. The definite advantages of PMBL machines are their inherently high efficiency, high power density, and high reliability. The key problem is their relatively high cost due to PM materials. In recent years, the class of PM BL drives has been expanded to embrace those with hybrid field excitations [**6**].

One example of successfully developed electric machines for HEVs is Interior Permanent Magnet Synchronous Machines (IPMSMs). This machine consists of large volume of PM as their main flux sources located in the rotor. The great merit of applying PM is to reduce the weight of the machine so that it can reduce the machine weight, hence increases the torque and power density of the machine [**7**]. This can be proved by the historical progress in the power density of main traction motor installed on Toyota HEVs, where 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 .

On the other hand, although the torque density of each motor has been changing hardly, a reduction gear has enabled to raise up the axle torque necessary for propelling the large vehicles such as RX400h and GS450h. Therefore, as one of the 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.

From this trend, IPMSM design tends to be difficult because all PM are placed on the rotor part and hence, to ensure the mechanical strength of rotor relies on the number of bridges and rib thickness between PM. Increase in the number of bridges would improve the mechanical strength, but, it would also reduce the maximum torque of the machine due to an increase in flux leakage. In addition, the parameters of the main machine part such as v-shape of PM, air gap slot on the rotor and armature coil slot shape are difficult to optimize.

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 reasonable cost

1.2 Problem Statement

In other situations, according to the report released by Mineral Resource Information Center (MRIC) associated to Japan Oil and Gas and Metals National Corporation, the increase in annual usage of rare-earth magnet has increased the price of Neodymium (Nd), Dysprosium (Dy) and Terbium (Tb) which are indispensable to provide the rare-earth magnet with high coercivity as the additives. Moreover, a future prospect was shortened such that the production amount of Nd2Fe14B would reach 1,500 tons only in HEV applications by 2012 and the corresponding usage of Dysprosium, 70 tons, would be a serious problem from the viewpoints of cost, security of the rare-earth materials and supply shortage. Therefore, the continuous researches and developments on a new machine with high power density, robust rotor structure for high-speed operation, and with no or less-rare-earth magnet machines would be very important [**8**].

As one alternate solution with high possibility to overcome this problem, a new design of 12Slot-14Pole field-excitation flux switching synchronous machine (FEFSSM) with no permanent magnet is proposed. Both FEC and armature coils are allocated at stator side. The rotor covers of only single piece iron, becoming more robust and more suitable for high speed operation. Although less pole number reduces the supply frequency of inverter, the 12Slot-14Pole machine is selected and proposed in this research because;

(1) it can be considered as the best minimum combination of slot-pole to avoid odd rotor pole numbers such as 6Slot-5Pole and 6Slot-7Pole machines yielding unbalanced pulling force,

(2) to avoid high torque ripples in case of 6Slot-8Pole and 6Slot-4Pole machines, and

(3) to take good balance between rotor and stator pole widths for minimizing inescapable torque pulsation.

1.3 Objectives

The objectives of this research is

i. To design the proposed 12Slot-14Pole inner rotor field excitation flux switching motor for electric vehicle applications.
ii. To analyze performance of the design motor under no load, load, torque, power and torque and power density of 12Slot-14Pole inner rotor field excitation flux switching motor (FEFSM) for electric vehicle applications motor
iii. To improve the performance of initial design of 12Slot-14Pole inner rotor field excitation flux switching motor (FEFSM) for electric vehicle applications.

1.4 Project Scopes

The scope of this project is

i. This project is design by using JMAG Designer version 13.
JMAG is simulation software for the development and design of electrical devices. JMAG incorporates simulation technology to accurately analyze a wide range of physical phenomenon that includes complicated geometry, various material properties, and the heat and structure at the center of electromagnetic fields. Besides, JMAG is also being used for the development of drive motors for electric vehicles.
ii. The design restriction and target specifications of the proposed machine for HEV compare with conventional IPMSM.

iii. The limit of the current density is set to the maximum of $30A_{rms}/mm^2$ for armature winding (J_a) and $30A/mm^2$ for excitation coil (J_e). The limit of current is set to maximum of 360A for armature winding(I_a) and 50A for excitation coil(I_e).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction To Flux Switching Motor (FSM)

In the middle of 1950s, the first concept of flux switching machine (FSM) was started and published [**9**]. In [**9**], a permanent magnet flux switching machine (PMFSM), i.e. permanent magnet (PM) single-phase limited angle actuator or more well-known as Laws relay, having 4 stator slots and 4 rotor poles was developed, while in [**10**] it was extended to a single phase generator having 4 stator slots, and 4 or 6 rotor poles. Over the last ten years or so, many novel and new FSM topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, aerospace, and etc.

Generally, the FSMs can be classified into three groups that are permanent magnet flux switching machine (PMFSM), field excitation flux switching machine (FEFSM), and hybrid excitation flux switching machine (HEFSM). Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources, while HEFSM contains both PM and FEC as their main flux sources. Fig. 1 clarifies the general classification of FSMs.

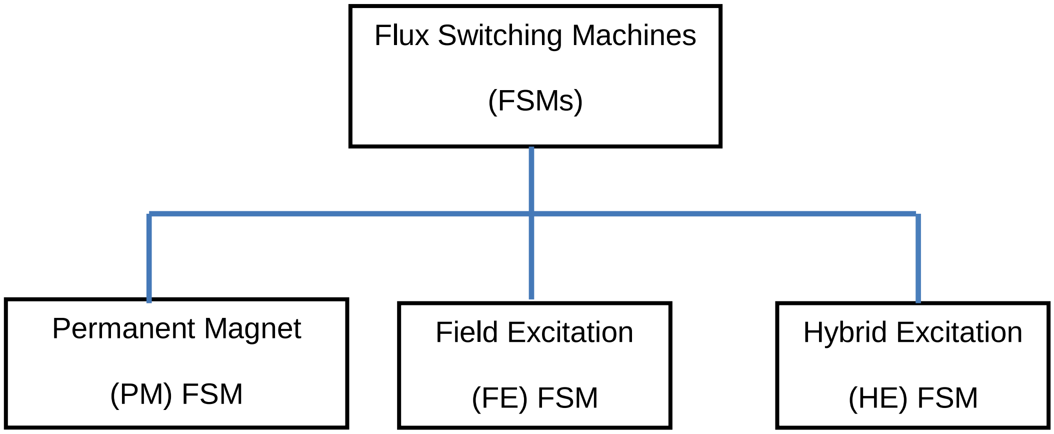


Fig. 2. 1:Classification of Flux Switching Machines

2.2 Permanent Magnet Flux Switching Motor (PMFSM)

The permanent magnet flux-switching machine (PMFSM) has a short history and is a relatively new category of electric machines. The basic model of PMFSM was designated in [**11**][18], where Rauch and Johnson proposed a new type of motor with permanent magnets placed in the stator in order to better control their temperature, and was brought back to the scene [**12**] due to a multitude of reasons, including the limit of permanent magnetic materials and the necessity of sophisticated computer-aided motor design tools. The PMFSM's have been receiving significant attention in the last two decades thanks to the advantages of high power density, mechanical robustness and torque capability. The PMFSM is very similar to the doubly salient permanent magnet (DSPM) machine or to the flux reversal machine (FRM) [**13**], [**14**]. The examples of three-phase PMFSM are illustrated in Fig. 2.2.

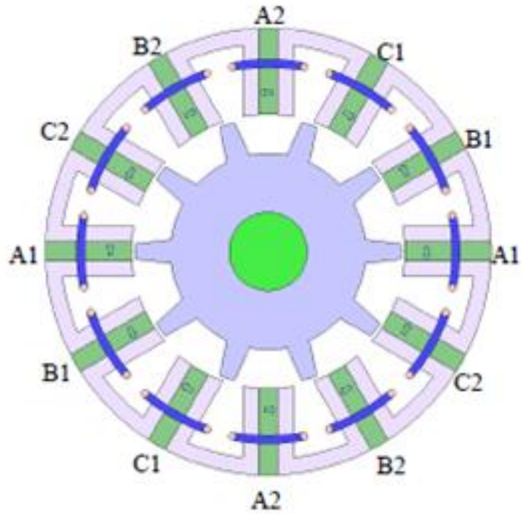


Fig. 2. 2: Examples of 12S-10P PMFSM

In other conditions, Permanent Magnet Flux Switching Machines (PMFSM) has been a popular research topic due to its high power density and robust rotor structure. With both permanent magnets and armature windings situated at the stator and robust single piece rotor similar to that of the switched reluctance machine, the PMFSM have benefits of ease cooling of all active parts such as armature coil and permanent magnets and better suitability for high speed application compared to conventional PM machines [**15**].

The general operating principle of the PMFSM is shown in Fig. 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 Fig. 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 Fig. 2.3(b), i.e., the flux-linkage switches polarity as the salient pole rotor rotates. In the conventional PMFSM, the stator copper area is significantly reduced since both the PMs and armature coils are housed in the stator with high PM volume employed.

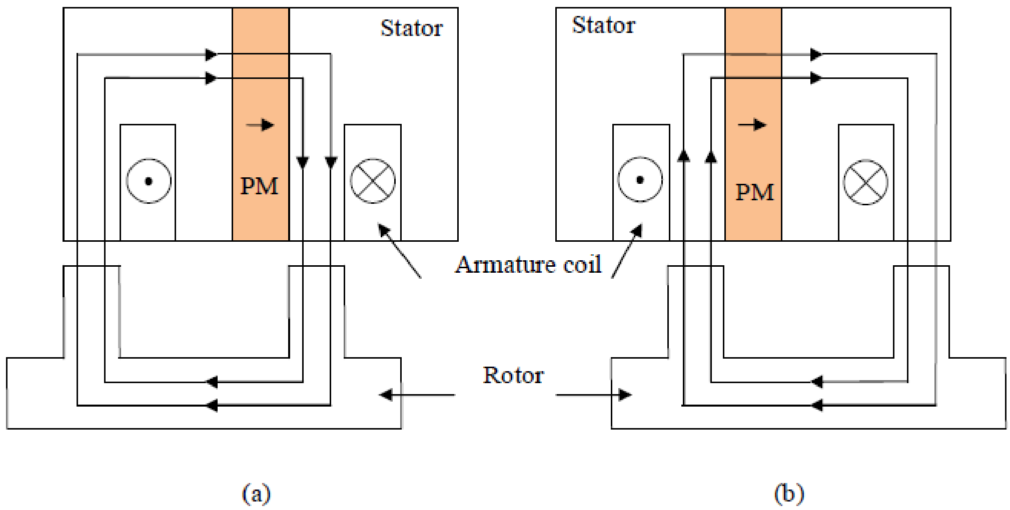


Fig. 2. 3: The principle operation of PMFSM

2.3 Hybrid Excitation Flux Switching Motor (HEFSM)

Hybrid excitation flux switching machines (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. By applying negative d-axis current, the PM flux can be counteracted but with the disadvantage of increase in copper loss and thereby reducing the efficiency, reduced power capability, and also possible irreversible demagnetization of the PMs. Thus, HEFSM is an alternative option where the advantages of both PM machines and DC FEC synchronous machines are combined. As such HEFSMs have the potential to improve flux weakening performance, power and torque density, variable flux capability, and efficiency which havebeen researched extensively over many years [**16**] [**17**] [**18**].

The combinations of stator slots and rotor poles for HEFSMs is illustrated in Fig. 2.4. Fig. 2.4 shows a 6S-4P HEFSM in which the active parts are arranged in three layers in the stator. The inner stator consists of the armature windings, followed by the FECs in the middle layer, while the PMs are placed in outer stator.

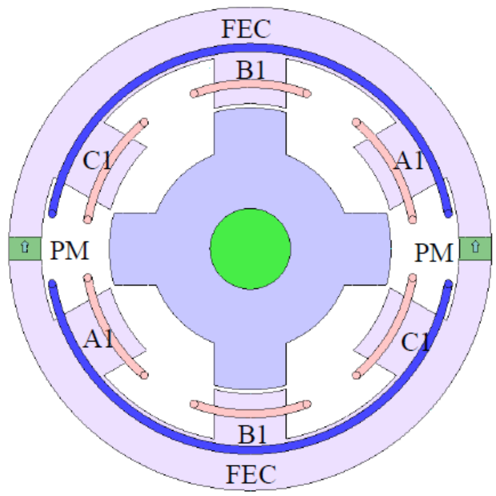


Fig. 2. 4: The example of 6Slot-4Pole HEFSM

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

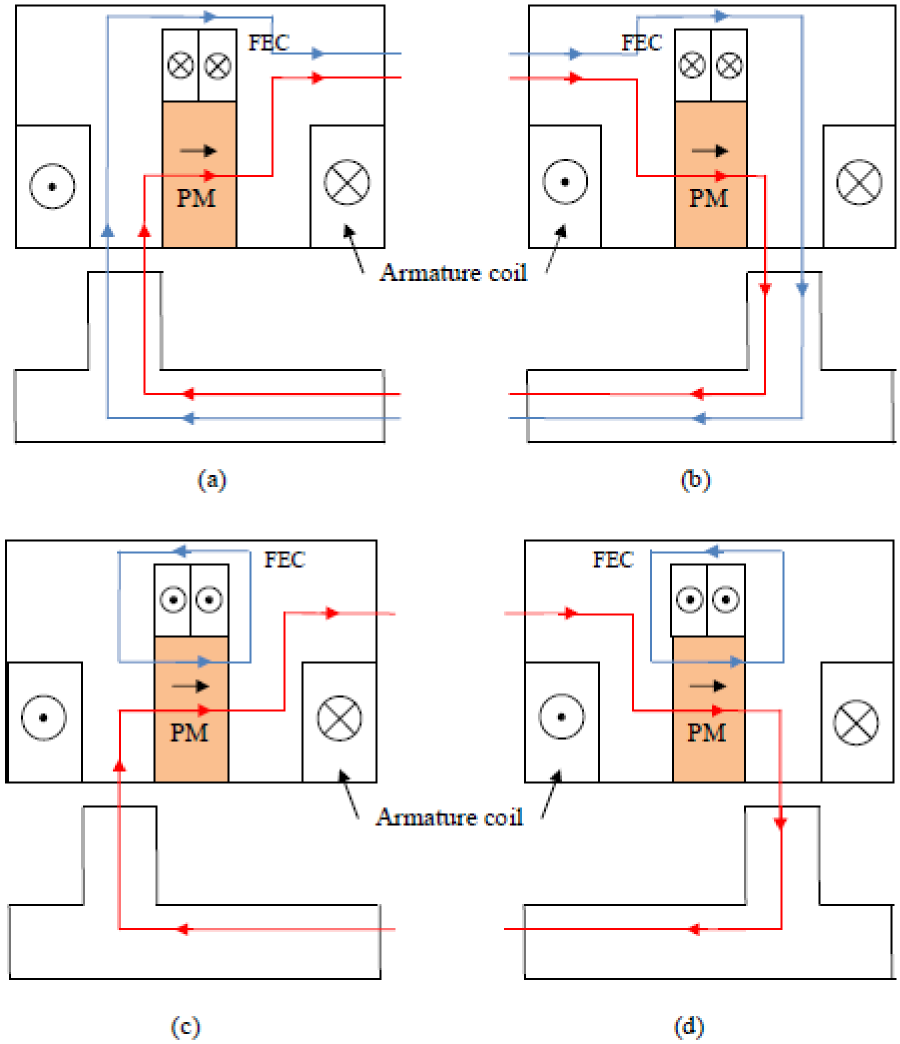


Fig. 2. 5: The operating principle of HEFSM (a) θ*e*=0° - more excitation (b) θ*e*=180° - more excitation (c) θ*e*=0° - less excitation (d) θ*e*=180° - less excitation.

The foregoing HEFSMs having magnets on the stator also suffers from one of 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

ii. The flux path of DC FEC significantly reduces the main flux excited by magnets and even short circuits the magnet flux

iii. Torque density may be significantly reduced due to less PM volume

2.4 Field Excitation Flux Switching Motor (FEFSM)

The PM excitation on the stator of conventional PMFSM can be easily replaced by DC FEC to form field excitation flux switching machine (FEFSM) as shown in Fig. 2.6. Among all FSMs, the FEFSM offers reward of magnet-less machine, low cost, simple construction, and variable flux control capabilities suitable for various performances. Moreover, to form the FEFSMs, the PM excitation on the stator of conventional PMFSMs can be easily changed by DC FEC as shown in Figs. 2 to 5. In other words, the FEFSM is a form of salient-rotor reluctance machine with a novel topology, combining the principles of the inductor generator and the SRMs [**19**].

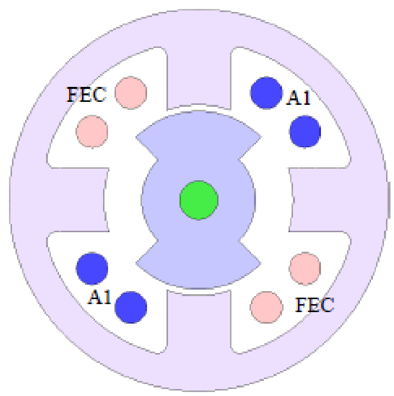


Fig. 2. 6: 1 phase 4Slot-2Pole FEFSM

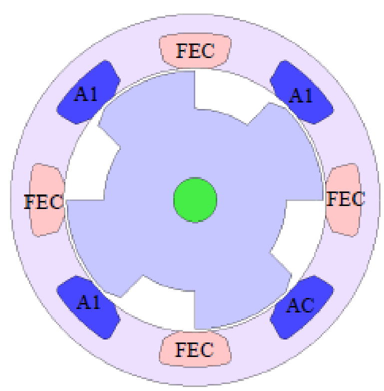


Fig. 2. 7: 1 phase 8Slot-4Pole FEFSM

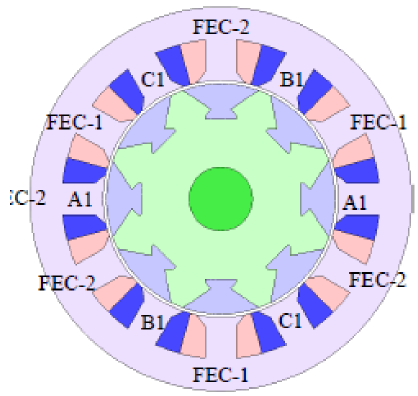


Fig. 2. 8: 3 phase 12Slot-8pole segmental rotor

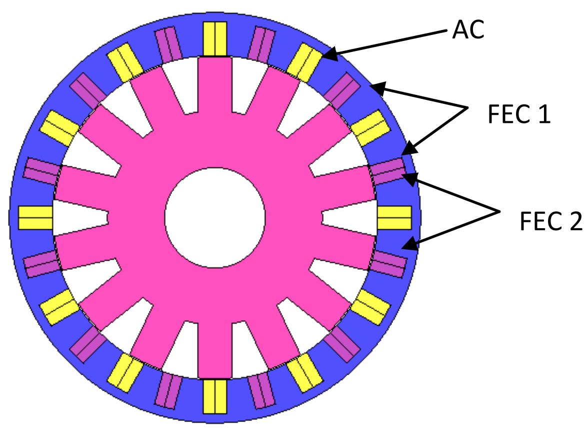


Fig. 2. 9: Initial design of 3 phase 12Slot-14Pole FEFSM

FEFSM involves changing the polarity of the flux linking with the armature winding, with respect to the rotor position. Early examples of single-phase 4S-2P FEFSM that employs with a DC FEC on the stator, a toothed-rotor structure and fully-pitched windings on the stator is shown in Fig. 2.6 [**11**]. From the figure, it is clear that two armature coil and FEC windings are placed in the stator which overlapped each other. The viability of this design was demonstrated in applications requiring high power densities and a good level of durability [**12**], [**20**].

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.

Another example of single-phase FEFSM is shown in Fig. 2.7 with eight stator slots and four rotor poles, 8S-4P FEFSM . From the figure, the FEC winding in four of the slots is fed with direct current to establish four pole magnetic fields. The other four slots contain an armature winding 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. Since 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[28]. The design principle is explained in [**21**], and the single-phase 8S- 4P FEFSM has achieved higher output power density than the equivalent induction motor. In addition, the machine also achieved much higher efficiency when compared with the induction machine. 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.

To improve the performances, a 3-phase 12S-8P with segmental rotor and 12S-14P FEFSMs have been developed as shown in Figs. 2.8 and 2.9, respectively. For 12S-8P FEFSM, segmental rotor is used to provide a clear magnetic path for conveying the field flux to adjacent stator armature coil following the rotor rotation. This design gives shorter end windings than the toothed-rotor structure which is associated with overlapping coils. There are significant gains with this arrangement as it uses less conductor materials and also can improve the overall machine efficiency [**22**].

The operating principle of the FEFSM is illustrated in Fig. 2.10. Fig. 2.10 (a) and (b)show the direction of the FEC fluxes into the rotor while Fig. 2.10 (c) and (d) illustrate thedirection 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 bythe transition between Fig. 2.10(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 insynchronism 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**].

Furthermore, the 12S-14P FEFSM is redesigned from the 12S-10P FEFSM is explained in [**1**] which the rotor is increased from 10 to 14 pole. The FECs produce six north poles combined between six south poles. The 12 slots armature coils contains of three phase supply located in each 1/4 stator body and is divided periodically. As the rotor rotates, the segments switch the armature flux so that it alternates up and down in these 12 slots. Each time the rotor rotates through 1/14 of a revolution, the flux linking the armature coils goes through a complete cycle, and so the frequency of the AC emf induced in the stator is 14 times the rotational frequency. This type of machine is categorized into flux switching synchronous machines (FSSM) which is also getting more popular and popular in recent years.

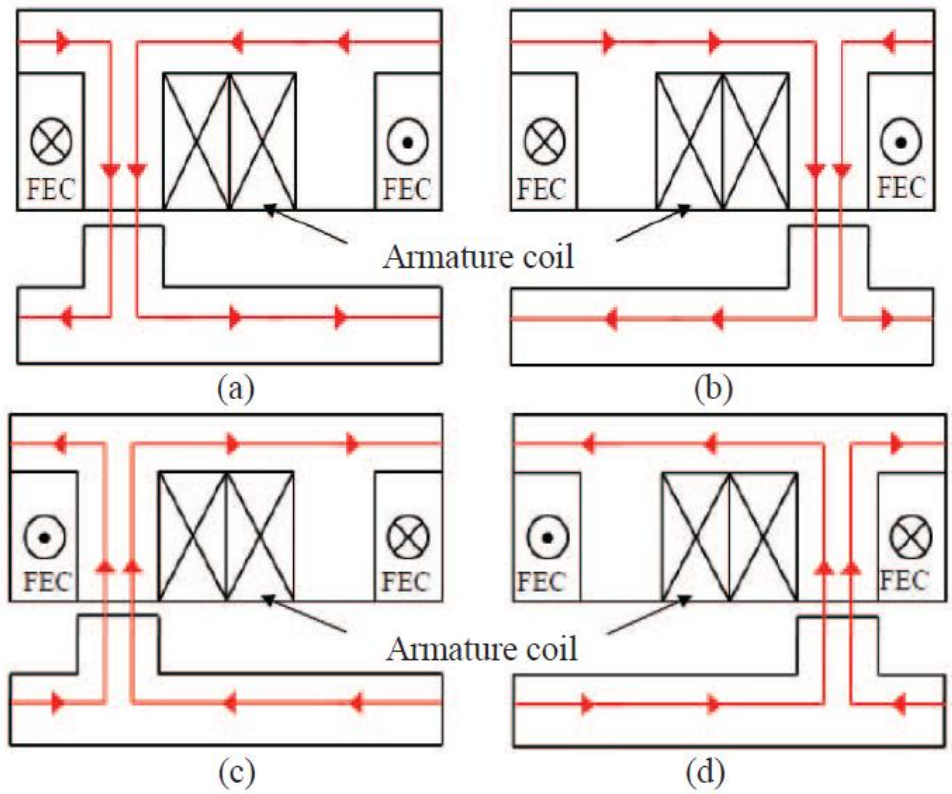


Fig. 2. 10: Principle operation of FEFSM (a) θe=0° and (b) θe=180° flux moves from stator torotor (c) θe=0° and (d) θe=180° flux moves from rotor to stator

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

Table 2. 1: Advantages and disadvantages of FSM

Advantages	Disadvantages
(i) Simple and robust rotor structure suitable for high speed applications	(i) Reduced copper slot area in stator
(ii) Easy to manage magnet temperature rise as all active parts are located in the stator	(ii) Low over-load capability due to heavy saturation
(iii) Flux focusing / low cost ferrite magnets can also be used	(iii) Complicated stator
(iv) Sinusoidal back-emf waveform	(iv) Flux leakage outside stator

which is suitable for brushless AC operation	
	(v) High magnet volume for PMFSM

2.5 Selected FEFSM Topology For HEV applications

In this thesis, based on the topology of FEFSM discussed in Fig. 2.9, the 12S-14P FEFSM is selected and proposed for HEV applications. Some design studies are conducted in the proposed 12S-14P FEFSM in effort to achieve the target performances of HEV considering design constraints and specifications of IPMSM used in Toyota HEV. Fig. 2.11 shows the original 12S-14P FEFSM. From the figure, it is obvious that the proposed 12S-14P FEFSM is composed of 12 FECs, distributed uniformly in the midst of each armature coil. The term, “flux switching”, is coined to describe that the stator tooth flux switches its polarity by following the motion of a salient pole rotor. In this machine, the FECs produce six north poles interspersed between six south poles. The three-phase armature coils are accommodated in the 12 slots. As the rotor rotates, the fluxes generated by mmf of the FECs link with the armature coil alternately. For the rotor rotation through 1/14 of a revolution, the flux linkage of the armature has one electrical periodic cycle and thus, the frequency of back-emf induced in the armature coil becomes fourteen times of the mechanical rotational frequency.

The relation between the mechanical rotation frequency and the electrical frequency for this machine can be expressed as:

$$f_e = N_r f_m \qquad 2.1$$

where, f_e is the electrical frequency, f_m is the mechanical rotation frequency and N_r is the number of rotor poles. The flux paths from mmf of FECs of the original design is depicted in Fig. 2.12. The dotted red line represents the flux from the FEC that presence of FEC makes these types of machines more attractive.

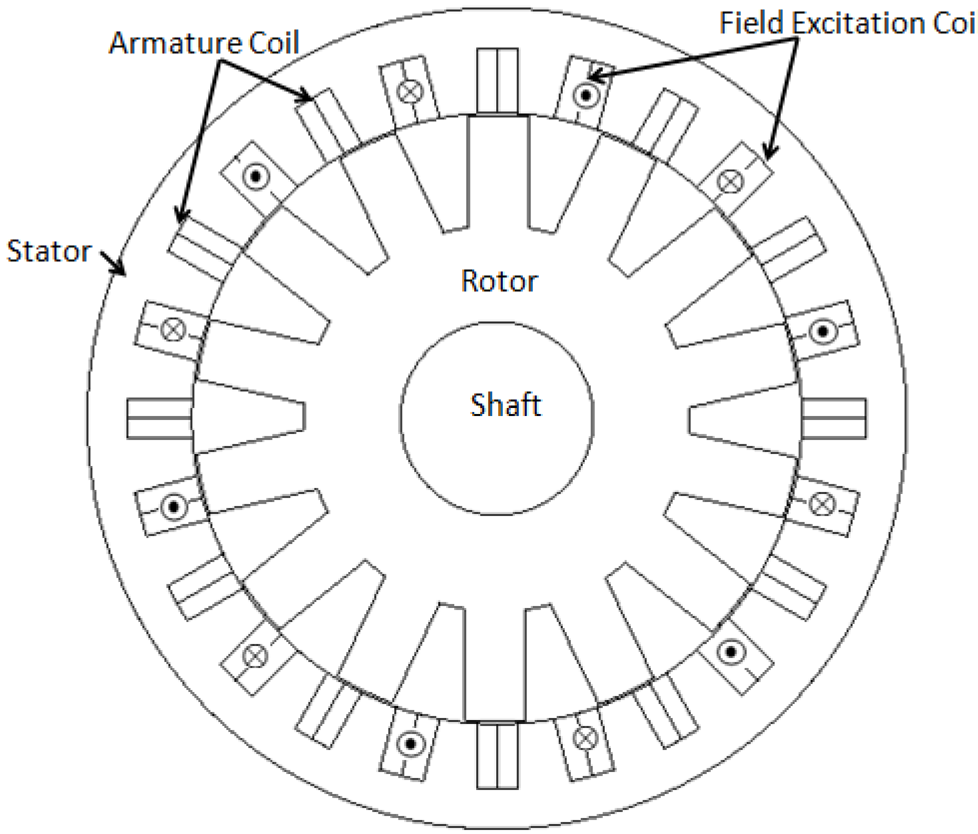


Fig. 2. 11: Original design of 12S-14P FEFSM

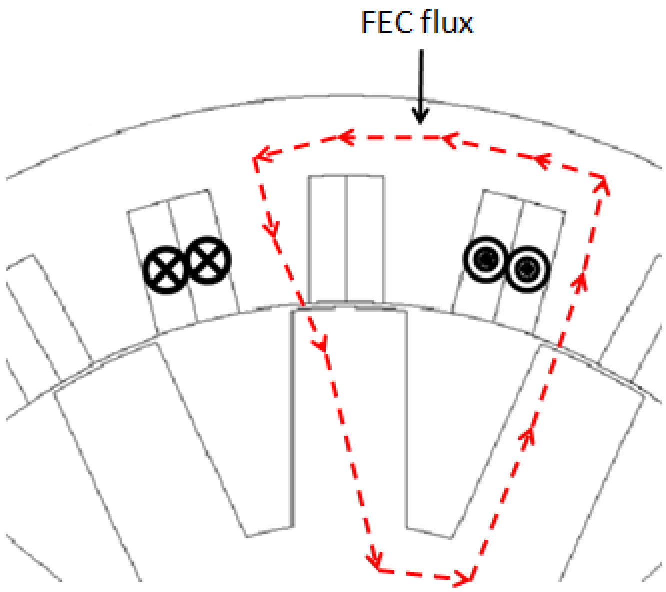


Fig. 2. 12: Flux paths of FEC of 12S-14P FEFSM

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Design Methodology

In this project, design study and flux interaction between FEC and armature coil of the 12S-14P FEFSM are investigated at no load. The machine configuration and dimensions (initial design) are illustrated in Fig. 3.1 and Table 3.1, respectively. Commercial FEA package, JMAG-Designer ver.13.0, released by Japan Research Institute (JRI) is used as 2D-FEA solver for this design. The design process of both parts is demonstrated in Fig. 3.2.

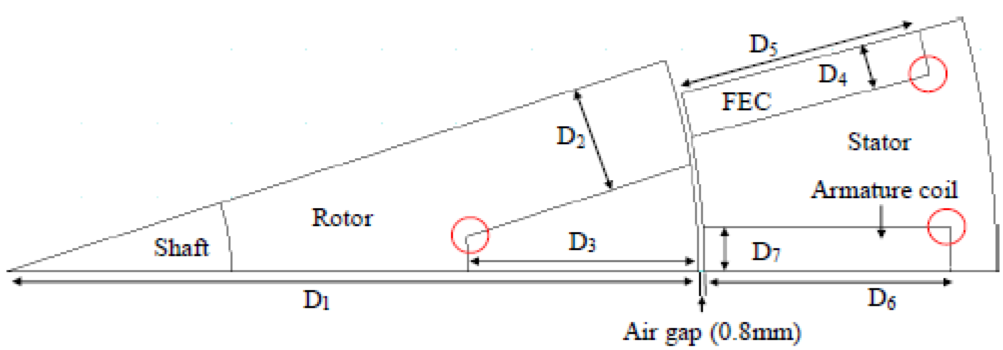
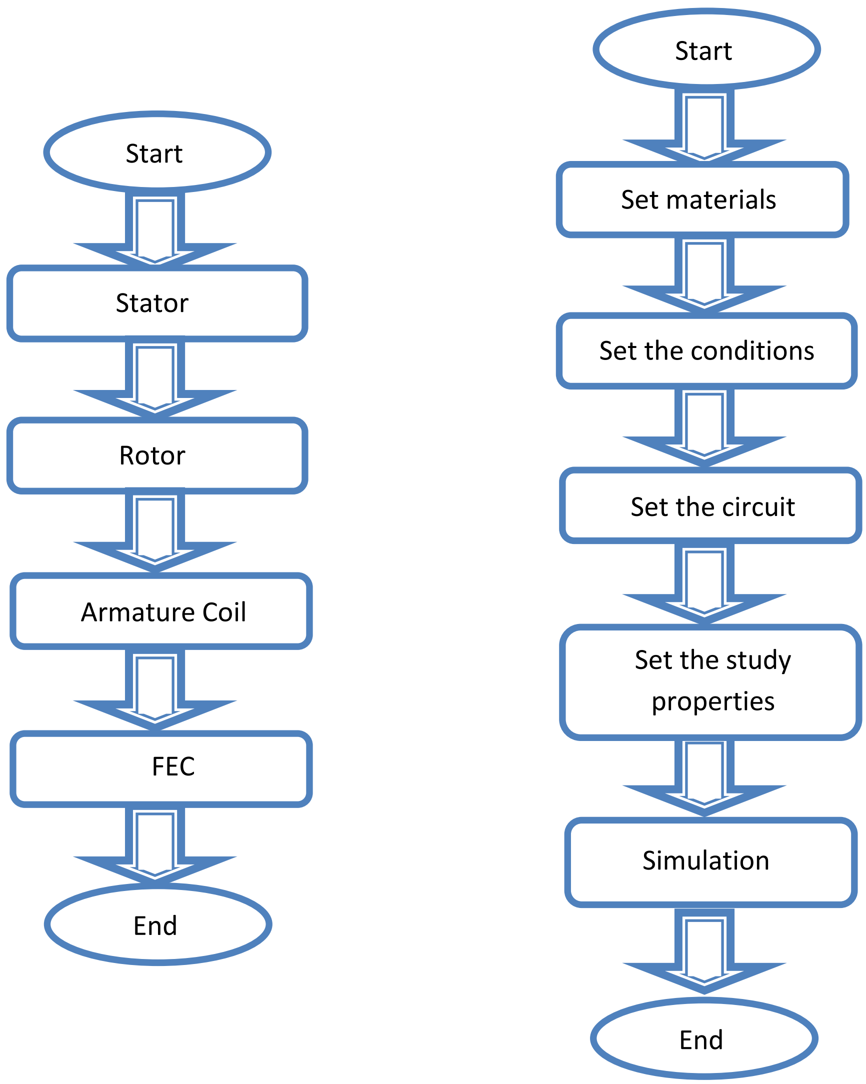


Fig 3. 1: Design parameter of 12S-14P FEFSM

Table 3. 1: 12Slot-14Pole FEFSM Parameter

Parameter	Details	Initial design
	No of phase	3
	No of stator Pole	12
	No of rotor pole	14
D_1	Rotor radius(mm)	96.2
D_2	Rotor pole width(mm)	10.5
D_3	Rotor pole depth(mm)	32.2
D_4	FEC Depth(mm)	20.0
D_5	FEC width(mm)	6.0
D_6	Armature coil depth(mm)	20.0
D_7	Armature coil height(mm)	7.2
N_a	No. of turns of Armature coil	6
S_a	Armature coil area(mm^2)	144.11
S_e	Excitation coil area(mm^2)	120.07
	Speed (rpm)	1200

Firstly, the rotor, stator, armature coil and Field excitation coil(FEC) of the proposed 12S-14P FEFSM is drawn by using JMAG Editor. Then, the materials, conditions, circuits and properties of the machine are set in JMAG Designer. Geometry editor is used to design each part of motor separately such as rotor, stator, armature coil and excitation coil while the condition setting and simulation are develop by using JMAG Designer.



(a) (b)

Fig 3. 2: Design methodology of the proposed 12Slot-14pole FEFSM (a) Parts drawing (b) Conditions setting

Initially the 30º mechanical angle of stator is designed with the following assumptions; (i) The air gap is set similar as the IPMSM which is 0.8 mm, hence the inner stator radius becomes 96.2 mm and this gives a stator depth of 25.6 mm, (ii) The stator pole depth is set to 20 mm (iii) The FEC slot area is set to 120.07 mm2 to give a maximum current density, J_e of 30 A/mm2 with 36 turns of FEC winding. The FEC slot depth is 6mm to give an appropriate distance between two FEC slots area for the flux to flow in this area, (iv) The armature slot area is set to 144.11mm^{2}to give the maximum current density J_a of 30A/mm^2 with 6 turns of armature coil winding. The armature depth is set to7.2mm overlapping between armature coil winding and FEC winding.

The design methodology of 12Slot-14Pole FEFSM using JMAG Designer is explained below.

Part 1: Geometry Editor (Parts drawing)

1. Geometry editor is used to design each part of motor separately such as rotor, stator, armature coil and excitation coil while the condition setting and simulation are develop by using JMAG Designer.
2. The work flow of geometry editor and JMAG Designer are illustrated in Figure 3.2.
3. Firstly, the 30^{o}stator pole is draw following the parameters in table 2 and the region is create as shown in Figure 3.3 and 3.4.
4. The region is mirror to make one stator pole by using the region mirror copy toolbar .
5. Region radial toolbar is used to make 12 stator poles as shown in figure 3.5.
6. For the rotor design, the 25.714^o rotor pole is draw and the region is created as shown in Figure 3.6.
7. The step 4 to 5 is repeated to complete the rotor drawing. Figure 3.7 is referred.
8. The drawing of field excitation coil is completed by refer to figure 3.8 and 3.9.
9. The last drawing is armature coil. The complete drawing of armature coil as shown in Figure 3.10 and 3.11.
10. The file is save. The model of 12Slot-14Pole motor drawing as shown in Figure 3.12.

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