DESIGN OF OUTER ROTOR FIELD EXCITATION FLUX SWITCHING MOTOR FOR DIRECT-DRIVE APPLICATION

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DEDICATION

To my beloved and lovely late mother, SAIDAH BINTI HAMDAN and my father, SYED OTHMAN BIN SYED IDRUS. My precious siblings, SYED ZULHILMI, SYED MOHAMAD IZZAT, SHARIFAH NORNAZUHA, SYED MOHAMAD AL-AZI, SHARIFAH NORHAIDA and lastly SHARIFAH NORUMAIRAH.

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ABSTRACT

This thesis contributes to a better understanding of the design and analysis of a 12S-14P three phase Outer Rotor Field Excitation Flux Switching Motor (OR-FEFSM) for direct-drive applications in Electric Vehicles (EV). Research work on the 12S-14P inner-rotor FEFSM carried out by others have reported a maximum torque figure of 226.12Nm and a power output of 127.61kW. The research work carried out in this thesis focuses on the design and analysis a class of 12S-nP three-phase Outer Rotor Field Excitation Flux Switching Motor (OR-FEFSM) configurations, where n is the number of poles of the motor. In particular, a total of five rotor pole configuration namely the 12S-10P, 12S-14P, 12S-16P, 12S-20P and 12S-22P configuration were investigated. Performance analysis of the torque and power versus speed characteristics were carried out using the Finite Element Analysis (FEA) software developed by JMAG Designer, version 13.0 which is able to calculate torque and power figures to six decimal places of accuracy. The optimum structure for OR-FEFSM was identified by conducting an extensive search in 2-D parameter space with constant diameter and stack length using the Deterministic Optimisation Method (DOM), which gives optimum output torque and power figures upon convergence. The simulation results obtained showed that 12S-14P was the optimal rotor pole configuration where a torque figure of 221.38 Nm and 186kW power output was obtained, which is 5.41% greater than the targeted performance specifications. The simulation results also showed that the 12S-14P rotor configuration can reach an efficiency figure as high as 73.33% in normal driving conditions.

ABSTRAK

Tesis ini menyumbangkan kepada pemahaman yang lebih baik bagi reka bentuk dan analisis 12S-14P tiga fasa Rotor Luar Pengujaan Medan Pensuisan Fluk (OR-FEFSM) untuk aplikasi pemacu terus Kenderaan Elektrik (EV). Kerja penyelidikan mengenai 12S-14P rotor dalam FEFSM yang dijalankan oleh penyelidik lain telah melaporkan angka tork maksimum 226.12Nm dan kuasa keluaran sebanyak 127.61kW. Kerja-kerja penyelidikan yang dijalankan di dalam tesis ini memberi tumpuan kepada reka bentuk dan analisis kelas 12S-nP konfigurasi tiga fasa Rotor Luar Pengujaan Medan Pensuisan Fluk (OR-FEFSM), di mana n adalah bilangan kutub motor. Khususnya, sejumlah lima kutub rotor konfigurasi iaitu 12S-10P, 12S-14P, 12S-16P, 12S-20P dan konfigurasi 12S-22P telah disiasat. Analisis prestasi tork dan kuasa berbanding ciri-ciri kelajuan telah dijalankan menggunakan perisian Analsis Unsur Terhingga (FEA) yang dibangunkan oleh JMAG Designer, versi 13.0 yang mampu untuk mengira tork dan kuasa angka enam tempat perpuluhan ketepatan. Struktur optimum untuk OR-FEFSM telah dikenal pasti melalui pencarian luas dalam ruang 2-D parameter dengan diameter yang kekal dan panjang timbunan menggunakan Kaedah Pengoptimum Berketentuan (DOM), yang memberikan output optimum tork dan kuasa angka penumpuan. Keputusan simulasi yang diperolehi menunjukkan 12S-14P adalah konfigurasi kutub rotor optimum di mana angka tork Nm 221,38 dan 186kW output kuasa telah diperolehi, iaitu 5.41% lebih besar daripada spesifikasi prestasi yang disasarkan. Keputusan simulasi juga menunjukkan bahawa konfigurasi rotor 12S-14P boleh mencapai angka kecekapan setinggi 73,33% dalam keadaan pemanduan biasa.

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In a world where environmental protection and energy conservation become concerns, the development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has taken on an accelerated pace. EV is a road vehicle that involves with electric propulsion. With this broad definition in mind, EV can be separated into battery electric vehicles (BEVs), HEVs, and fuel-cell electric vehicles (FCEVs). Alternatively, an EV can be categorised according to the type of propulsion whether it is a pure electric motor drive or electric motor drive and internal combustion engine (hybrid). Moreover, it can also be related with the energy system that it used to power the vehicle such as battery, fuel cell, or ultra-capacitor, and the energy source and infrastructure of the EV whether by electric grid charging facilities, gasoline station, or hydrogen [1]. Electric propulsion consists of the motor drive, transmission device, and wheels. In fact, the motor drive, comprising the electric motor, power converter, and electronic controller is the core of the EV propulsion system. Thus, the desirable features of the EV motor drive can be summarised as follows:

(i) High power density
(ii) High pull-up torque and high power for cruising
(iii) Wide speed range for constant torque and power region
(iv) Fast torque response
(v) High efficiency
(vi) High reliability and robustness
(vii) Reasonable cost

Electrical motor can be categorised into Direct Current (DC), and Alternating Current (AC). Moreover, an AC can be further categorised into Induction Motor (IM), Switch Reluctance Motor (SRM), and Synchronous Motor (SM) [2]. However, the DC motor has a commutator; hence, it requires regular maintenance. Thereby, a non-commutator motor are becoming attractive because of high reliability and maintenance-free operation, thus it has become a prime consideration for EV. Besides, there are two types of rotor configurations for electric motor, the inner-rotor and outer-rotor configuration.

Likewise, the IM has been widely used because of its non-commutator design but the system normally runs into problems related to temperature rise, high loss, low efficiency, low power factor, and low usage factor of the inverter, which is more serious for the high-speed, large-power motor [3]. Moreover, the induction motor provides the solution of none magnet motor designs because its rotation is caused by the induction magnetomotive force (MMF) and the structure is very simple and robust. This is for typical inner-rotor induction motors that have already been developed. For the outer-rotor IMs, they have already been developed and optimised to expand the usage of EV [4] .

The next type of electric motor is the SRM, which has an extremely simple and robust structure without any permanent magnets, and high heat capability. Therefore, these advantages are suitable for the application of an in-wheel direct drive, known as outer-rotor Switch Reluctance (SR) motor for EVs [5].

Interior Permanent Magnet Synchronous Motors (IPMSM) have been widely used because they have some advantages such as high efficiency, high torque, and comparatively easy speed control. Furthermore, an IPMSM with concentrated winding has been used instead of the ones with distributed winding. The copper loss of concentrated winding motor is lower than distributed winding motor and the size of concentrated winding motor is smaller compared with distributed winding motor [6]. In recent years, it has been noticed that the outer rotor type of IPMSM has a higher torque than the inner rotor type. An IPMSM that has been successfully developed even for a small size motor is the air-conditioning system [7]. Moreover, IPMSM is employed as a main traction because of its characteristics to operate over a wide area of torque-speed region. One example of IPMSM developed by Toyota and employed for HEV is the Lexus RX400h'05 and GS450h'06 that have been much improved compared with Prius'97 [8].

In the Toyota Hybrid System II developed in 2005 for SUV, DC bus voltage was boosted up to 650V and reduction in size with over twice the ratio [9], [10]. Despite IPMSM having good performances and being well operated, there are still some major drawbacks. For example, it has many mechanical weak points due to the high number of bridges, high volume of Permanent Magnet (PM) used, and the complex structure that increases the development cost [11].

As an alternative, a performance analysis without PM had been studied recently but with armature coil and field excitation coils as the main mmf source. Conversely, Field Excitation Flux Switching Motor (FEFSM) design is able to compete with IPMSM maximum torque, at 210 Nm and power density of 3.5 kW/kg. It is composed of a rotor with a stack of iron, hence it is robust and suitable for high-speed operation at 20,000 r/min [12]. Figure 1.1 illustrates the example of DC motor, induction motor, switch reluctance motor, and interior permanent magnet synchronous motor topology [16].

A good efficiency should be a priority for every electrical machine operating within traction systems. The desired performances (high torque or wide speed) for each drive system are always accompanied by electro-mechanical necessities, translated in terms of high levels of power factor and efficiency. The EV industry is developing quickly because of environmental interests and legislative pressure. One of the radical proposals is the in-wheel mounted motor.

This is a direct-drive solution whereby all mechanical transmissions and differentials are eliminated [13]. It also requires a low-speed but high-torque motor performance. The advantages resulted from the direct-drive arrangement are significant reduction of the vehicle weight and an improvement in the drive's overall efficiency. However, the wheel direct-drive application has a very high torque-weight ratio and efficiency to limit the mass stressing of the wheel suspension and gains the benefits envisaged in terms of drive efficiency [14], [15].

Therefore, a better design of an electric motor for application of direct-drive configuration is that the electric motor should have a good performance with high torque and power density. Furthermore, an economical motor such as a non-permanent magnet, a simple construction with a small size and low weight, would be very beneficial.

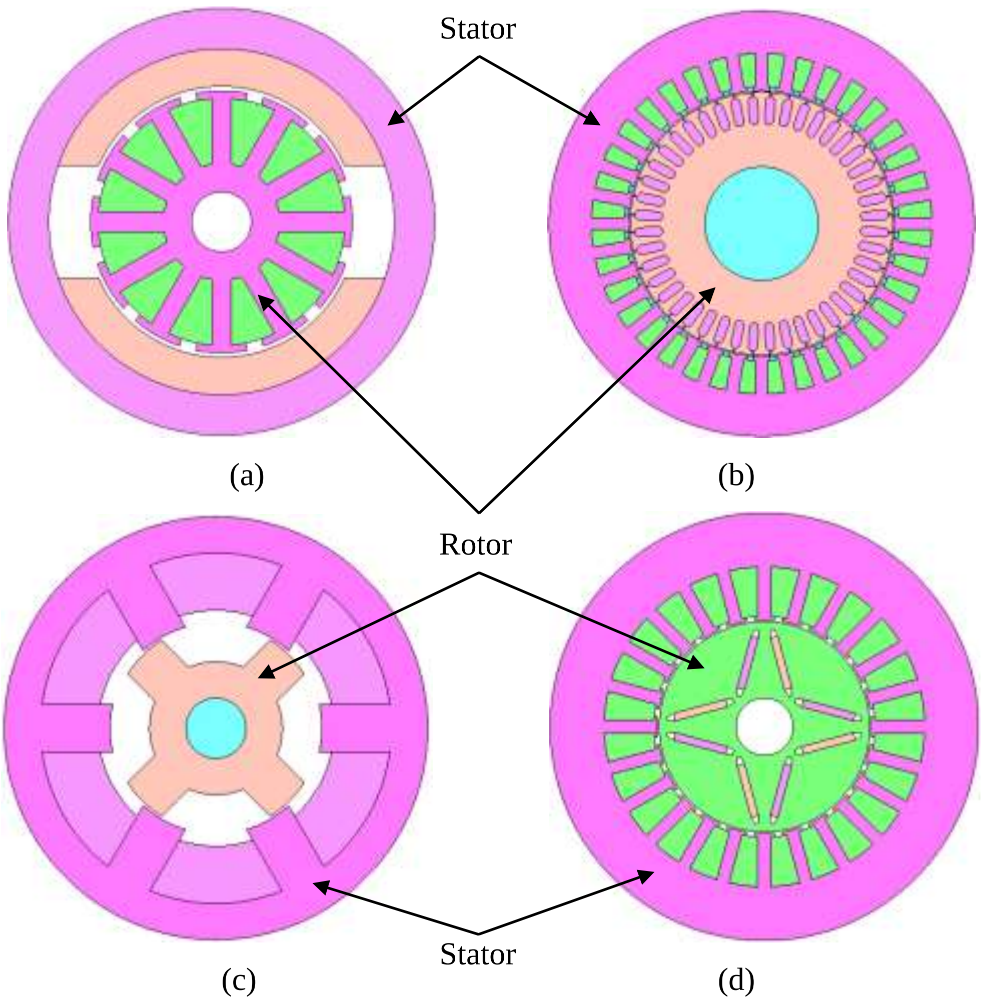

Figure 1.1: Example of (a) DC motor (b) Induction Motor (c) Switch Reluctant Motor (d) Interior Permanent Magnet Synchronous Motor [16]

1.2 Problem Statement

IPMSM structures are more complex with the existence of PM at the rotor and armature coil at the stator. Hence, IPMSM is not robust because of the PM positioned at the rotor. This could increase the cost of fabricating a complex structure. Other related works have been done, for example a three-phase FEFSM are developed from 12S-10P PMFSM in which the PM is removed from the stator and replaced with DC-FEC. The problem is that an inner rotor of the three-phase 12S-10P FEFSM produces low torque theoretically because of the low moment arm. Besides, an inner rotor of a motor is a drawback to EV especially on the transmission system, shaft, transaxles, clutches, and reduction gears, which lead to high weight of the vehicle, complex mechanical design, and power losses. Hence, by integrating the motor into in-wheel, it can eliminate the need for shafts, transaxles, differentials, clutches, and reduction gears, thereby eliminating transmission losses, reducing the weight of the vehicle, and also simplifying the mechanical design of a full EV. To overcome this problem, an alternative design of an outer-rotor configuration, such as a simple and robust motor is needed, such as an outer-rotor field excitation flux switching motor (OR-FEFSM).

1.3 Objectives of the Study

Objectives of this research are:

(i) To design a number of slot-pole for a three-phase outer-rotor field excitation flux switching machine (OR-FEFSM) as a new candidate for direct-drive application.

(ii) To investigate the performances of three-phase OR-FEFSM in terms of its torque and speed characteristics.

(iii) To optimise the initial design structure of OR-FEFSM for a much higher torque and speed performance.

1.4 Scopes

Design restrictions, target specification, and parameters of proposed three-phase OR-FEFSM for direct-drive application are divided into three parts based on the objectives:

(i) Motor Design and Geometry

The study is being done using JMAG ver. 13.0, released by Japan Research Institute (JRI). All the proposed design parameters, restrictions, and target specifications of the three-phase OR-FEFSM is in Table 1.1 [17]. From Table 1.1, most of the OR-FEFSM geometry follows the geometry of IPMSM. For the initial design, outer diameter, motor stack length, shaft radius, and air gap of the main part of the machine design are 264 mm, 70 mm, 30 mm, and 0.8 mm respectively. These parameters are identical with IPMSM [20].

(ii) Electrical Specification for No-Load Analysis and Load Analysis

The electrical restrictions related to the inverter has a maximum of 650V DC bus voltage and a maximum of 360 A of current. Assuming that the water jacket system is employed as the cooling system for the machine, the limit of the current density is set to a maximum of $30A_{rms}/mm^2$ for armature winding and $30A/mm^2$ for FEC, respectively [18].

(iii) Rotor Poles Analysis and Optimisation Method

The five different rotor poles performance, 12S-10P, 12S-14P, 12S-16P, 12S-20P, and 12S-22P, are chosen based on its performance during no-load and load condition. The target maximum operating speed is 20,000r/min based on the assumption that the rotor structure is mechanically robust to rotate at high speed because it consists of only stacked soft iron sheets. After the initial design had undergone the no-load and load condition, the best two designs are chosen for optimisation. Based on simple and agreeing [19] the deterministic method for optimisation is chosen from several other methods including the genetic algorithm method. Hence, deterministic method is able to analyse the performance of the electric motor with each parameter change is compared with the global optimisation method.

Table 1.1: Design Restrictions and Specifications of OR-FEFSMs [17]

Specification	IPMSM	3ϕ OR-FEFSM
Inverter		
Max. DC-bus voltage inverter (V)	650	650
Max. inverter current (A_{rms})	Conf.	360
Max. current density in armature winding, J_A (A_{rms}/mm^2)	Conf.	30
Max. current density in excitation winding, J_E (A/mm^2)	NA	30
Geometrical		
Stator outer diameter (mm)	264	264
Motor stack length (mm)	70	70
PM weight (kg)	1.1	0
Air gap length (mm)	0.8	0.8
Targeted		
Maximum speed (r/min)	12,400	>12,400
Maximum torque (Nm)	333	>210
Maximum power (kW)	123	>123

1.5 Thesis Outline

This thesis presents the research on the three-phase OR-FEFSM for direct-drive applications. It is separated into five chapters and the summary of each chapter will be explained here. In the first chapter, there will be an introduction about the research on viable candidates for EV drives and a simple explanation regarding the existing of IPMSM used in HEV and its drawbacks. The research objectives and scopes are also listed in this chapter.

The second chapter will explain more details on previous and current researches of FSM that have been established either for inner or outer rotor including the operating principle of the proposed OR-FEFSM for direct-drive applications. The third chapter describes the design restrictions and specifications of the proposed OR-FEFSM with similar restrictions and specifications of IPMSM used in HEV. Equations are listed and presented in order to determine the suitable slot-pole combinations, end time, and also frequency for each slot-pole combinations.

Based on the objectives, this chapter is separated into three major parts. The first part discusses the design configuration and geometry. The second chapter discusses the performances in no-load and load condition of 12S-10P, 12S-14P, 12S-16p, 12S-20P, and 12S-22P and presents the result comparison between the initial and optimum design of OR-FEFSMs. The last chapter concludes the research and points out future works for design improvements, for example, the shape improvement of the armature and field excitation slot for increasing the flux linkage.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 presents the detailed discussion about synchronous motor (SM) especially on the flux switching motor (FSM). It explains the operation of flux switching motor varied with hybrid-excitation, permanent magnet excitation, and field-excitation motor. Moreover, this chapter focuses more about the outer-rotor configuration of FSM. The explanation on the advantages and disadvantages of the proposed OR-FEFSM is also discussed.

2.2 Introduction to Electric Motor used in Electric Vehicle

An electric motor is a device that can convert electrical energy to mechanical energy. Electric motors used in EV can be classified either as indirect-driven or direct-driven motors. Some direct-driven motors are designed as in wheel motors or hub motors. These type of motor are directly mounted inside the wheels. These motors do not use transmission gears or mechanical differential gears for mechanical power transmission, which contributes to additional power losses. The elimination of mechanical components such as transmission chains and gears not only improves the overall efficiency, but also reduces the weight of the vehicle.

Furthermore, an electric motor can be classified into two types, the Direct-Current (DC) powered electric motor and Alternating-Current (AC) powered electric motor. Most electric motors operate based on the reaction between magnetic and current-carrying conductor that generates force. Electric motors are always associated with rotating coils, which are driven by the magnetic force. This force is produced by a reaction between a magnetic field and a magnetic current. Equation (2.1) and Equation (2.2) show the voltage and torque of DC motor respectively.

$$E = E_b + I_a R_a \tag{2.1}$$

$$T = k_a \phi I_a \tag{2.2}$$

$$k_a = \frac{Zp}{2\pi a} \tag{2.3}$$

where E is the voltage applied, E_b is back emf produce, I_a and R_a is the armature current and resistance respectively, T is the torque produced, where k_a depends on the machine construction, and ϕ is the flux produced. The presence of the commutators and brush gear for DC motor will cause sparking and brush wear problems, requiring frequent maintenance. The use of speed-reduction gears also lowers the drive efficiency and increases the weight of the drive train. To overcome these problems, a brushless in-wheel DC motor drive may be employed. Brushless motors provide less maintenance, long life, and quiet operation. They produce more output power per frame size than PM or shunt wound motors and gear motors. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult [19].

DC motor is widely accepted for HEV drives because they can use a battery as a DC supply. It has an advantage of simple control principle, but the problem caused by the commutator and brush makes them less reliable and unsuitable for maintenance-free drives. In the class of direct-driven motors, the axial-flux motors have additional advantages over radial-flux motors. These include more balanced motor torque, better heat removal configuration, and adjustable air gap. Moreover, brushless DC motor with surface-mounted permanent magnet can be designed for higher torque-to-weight ratio and higher efficiency [20].

AC motors do not require brushes, hence they are very rugged and have long life expectancy. In addition, the speed of an AC motor is controlled by varying the frequency, which is done with an adjustable frequency drive control. Presently, there are three types of AC motor, which are the Induction Motor (IM), the Synchronous Motor (SM), and the Switched Reluctance Motor (SRM). An IM is well suited for applications that requires constant speed operation. It is made up of a stator and a rotor. It is called “IMs” because the rotor voltage is induced in the rotor windings instead of physically connected by wires.

SRMs do not contain any permanent magnets and the operation of the stator is the same as brushless DC motor while the rotor is only consisted of a laminating iron. The operation of the SRM where the salient poles tend to align to minimise reluctance in normal operation leads to high normal forces acting on the stator structure. The harmonics of these normal forces will resonate with the natural frequency resonant modes of the stator structure thus producing acoustic noise [21]

As for in-wheel application, a novel SRM motor consists of a dual stator and a single rotor. The rolled-out model of the motor shows the actual motor has a double concentric stator structure with a 'yokeless' rotor embodied in between the two stator members. Motoring operation relies on the fundamental mechanism of reluctance torque generation in which the motor's magnetic saliency is exploited to create alignment torque. As the stator is electromagnetically energised, the rotating part moves to restore minimum reluctance or maximum inductance. A novel feature of the new motor, however, rests on a unique stator and rotor configuration that allows flux formation in the magnetically isolated yokeless rotor teeth. This results in virtually all iron parts on the rotor being used for active torque generation. Alignment forces are produced on the rotor teeth located along the circumference of the yokeless rotor, when flux is established by yoke-less (less yoke) stator pole pairs [22]. Another example is the four-wheel independent drive configuration, within every wheel there can be one direct-drive in-wheel SRM motor to generate the necessary torque per wheel [23].

SMs are AC motors that have a field circuit supplied by an external DC source. The stator has electromagnets resulting in the creation of magnetic field, which rotates in time with the oscillations of the line current. The rotation period of SM is exactly equal to an integral number of AC cycles. Equation (2.3) and Equation (2.4) shows the speed and voltage of synchronous motors.

$$n = \frac{120f}{N} \tag{2.3}$$

$$V = ri + \frac{d\Phi}{dt} \tag{2.4}$$

Where *n* is the mechanical rate of rotation, *f* is the stator electrical frequency and *N* is the number of poles in the motor. SMs can be classified as Permanent Magnet (PMSM), Field Excitation (FESM), Hybrid Excitation (HESM), and Flux Switching Motor (FSM). Examples of PMSM for in-wheel application are the surface-mounted PM and auxiliary field winding [24]. Figure 2.1 illustrates the classification of main types of electric motors.

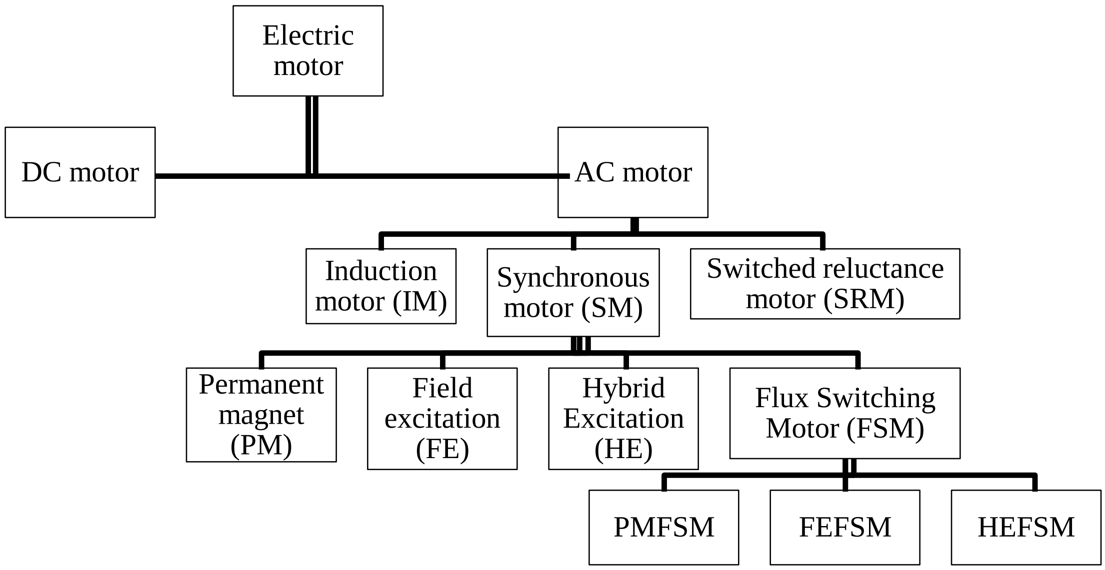

Figure 2.1: The Classification of the main types of Electric Motors

2.3 Review on Direct-Drive Application used in Electric Vehicles

A novel for EV with four in-wheel direct-driving motor for high performance have been developed to achieve high performance characteristics. The in-wheel motors are composed of an outer rotor with a rare-earth PM (Sm-CO) and an inner stator. The motor drive controller consists of a three-phase inverter and a microprocessor-based controller. The maximum output and maximum torque of each total drive system, including motor and inverter, are 25 kW and 42.5 kNm, respectively, and the total efficiency of the drive system is over 90% at the rated speed. The general description of the EV is four motors drive the wheels directly without mechanical gear, motors are synchronous motors with PMs, and are placed inside the wheels and controlled current inverters are employed for each motor [25].

Another example is the high-power density electric drive for HEV, whereby each wheel of the vehicle is fitted with a 12-pole, three-phase, PM motor with surface-mounted magnets, and an integral speed reducer packaged within the hollow rotor. Each PM motor is rated at 9kW (3560rpm) and 29kW peak continuously. The PM-Brushless motors have trapezoidal emf, which are supplied with 120" quasi-square wave currents from the IGBT inverters operating at 18kHz PWM frequency [26].

One example of a successfully developed electric machines for HEVs is IPMSM, which has been employed primarily to increase the power density of the machines [27]. In spite of their good performances and operation, IPMSMs installed in HEV have some demerits such as the present IPMSM that has a multifaceted shape and structure, which are quite complicated to perform the design optimisation. Secondly, the constant flux from PM is hard to control especially at light load with high-speed operating points. In the meantime, the volume of PM used in IPMSM is very high, which increases the expenditure of the machine.

2.4 Overview and Classification of Flux Switching Motor (FSM)

The principle or term “flux switching” comes from the mid-1950s by sample design based on the combination of a single-phase alternator and a PM excitation [28]. From here on, more and more researchers study on applying principle flux switch to design an electric machine either generator or a motor. Hence, technologies in this day have shown a tremendous advance on various applications for example automotive industry like the HEV and EV. Generally, the flux switching motor (FSM) can be categorised into three groups: permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM). Figure 2.2 illustrates the classification of FSM.

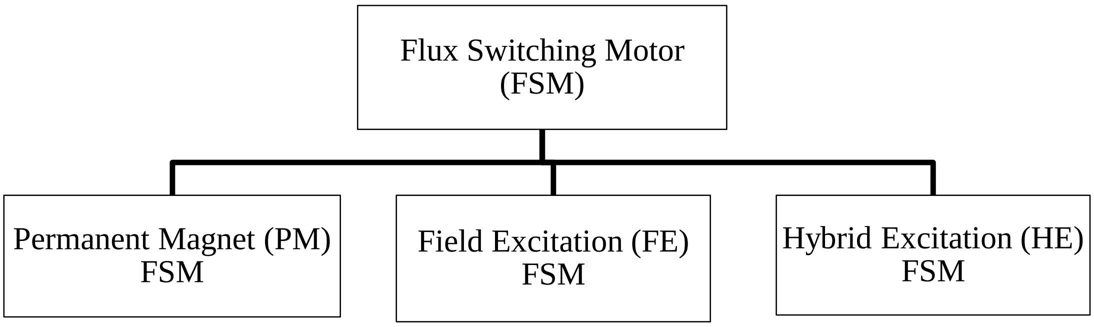

Figure 2.2: Basic structure for Flux Switching Motor (FSM) [37]

The basic structure of FSM consists of the rotor, stator, armature coil, and PM for PMFSM, or DC-FEC for FEFSM and HEFSM, which have both PM and DC-FEC. An example of the basic structure for each FEFSM, PMFSM and HEFSM is explained in Figure 2.4, Figure 2.5, and Figure 2.6. The rotor consists of only a single structure, which is the iron core, thus allowing its simple construction and inherent robustness to be retained while both field and armature windings are on the stator. These contribute to major advantages where all brushes are eliminated, while complete control is maintained over the field flux. The operation of the motor is based on the principle of switching flux. The term "flux switching" is created to describe machines in which the stator tooth flux switches polarity following the motion of a salient pole rotor [29]. All excitation sources are on the stator with the armature and field allocated to alternate stator teeth.

Flux is produced in the stator of the machine by PM or by DC current flowing in the field winding. The orientation of the field flux is then simply switched from one set of stator poles to the next set by reversing the polarity of the current in the armature winding. In the case of inner-rotor flux FSM, the rotor pole number, N_r is normally designed as close to stator slot number, N_s to maximised the performances of the machine [30]. An appropriate number of pole for the machines must be determined to find the optimal performance. As studied in [31]–[33], the analysis has done for N_r ranges from 14 to 26 and N_s is fixed at 12. All of them concluded their analysis by choosing 12S-22P as the most suitable for the proposed three-phase outer rotor PMFSM because N_r equal 22 exhibits the highest back-emf and lowest cogging torque.

However, the analysis presented is only focused on the principle of back-emf and cogging torque characteristic.

Other parameters such as generated magnetic flux, output torque, and power need to be investigated to find the optimal performances and suitable to be further optimised [34]. As the proposed motor is designed for HEV applications, the high torque and power density capabilities are important parameters besides the back-emf and cogging torque.

2.4.1 Permanent Magnet Flux Switching Motor (PMFSM)

Over the past decade, many automotive companies have been commercialising HEV or EV using rare-earth magnet as the main flux source, resulting in the development of Permanent Magnet Flux Switching Motor (PMFSM). This is due to the restriction of the motor size to ensure enough passenger space and the limitation of motor weight to reduce fuel consumption [35]–[37]. In other circumstances, PMFSM has been a popular research topic due to its high power density and robust rotor structure. With both PMs and armature windings located at the stator and robust single piece rotor similar to that of the switched reluctance machine, PMFSM has the advantages of easy cooling of all active parts, and suitability for high-speed drives compared with conventional PM machines [38], [39]. The vector control of the PMFSM is derived from its dynamic model. Considering the currents as inputs, the three currents and torque are shown in Equations (2.5), (2.6), (2.7), and (2.8) respectively [26].

$$I_a = I_m \sin(\omega_r t - \Theta) \tag{2.5}$$

$$I_b = I_m \sin(\omega_r t - 120° - \Theta) \tag{2.6}$$

$$I_c = I_m \sin(\omega_r t - 240 - \Theta \tag{2.7}$$

$$T = \frac{3}{2}.\frac{P}{2} \left\{\frac{1}{2} I_m^2 \sin 2\alpha\, \lambda_f I_m \sin\alpha\right\} \tag{2.8}$$

Where, I_a , $I_{b\ \mathrm{and}}$ I_c is the current of each phase and I_m is the peak current, α is the angle between the rotor field and stator current phases, ω_r is the electrical rotor speed.

Unfortunately, the generated flux produced is fixed and will not change-diverged, which means it has a constant flux because of the characteristics of the PM. In the meantime, in proportion of HEV getting popular, the increase of the usage of rare-earth magnet results in the increase of price. This would cause serious concern about high cost. 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 [40].

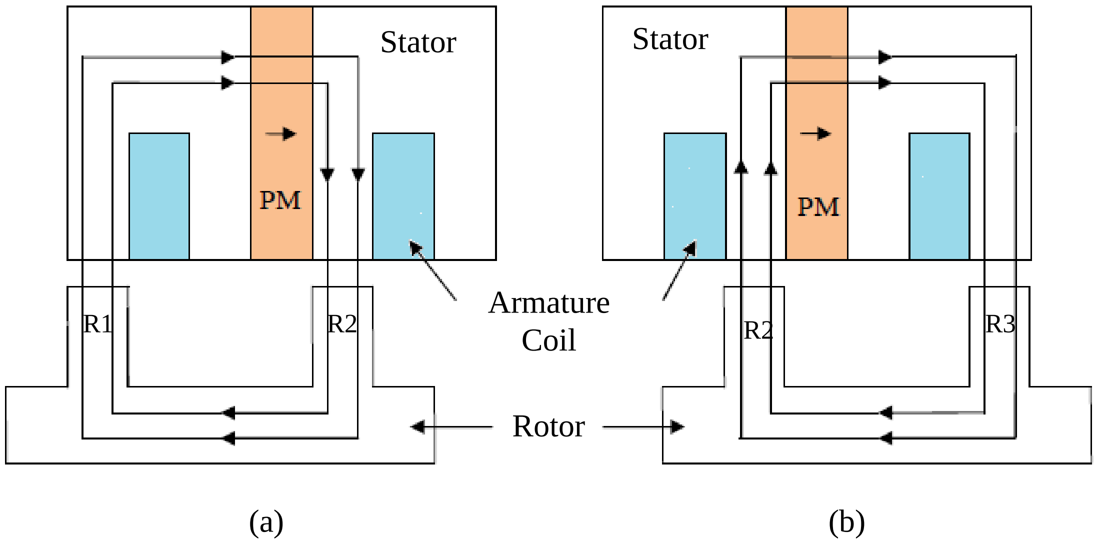

Figure 2.3: Principle operation of PMFSM (a) Flux linkage correspond to one polarity (b) Flux linkage switch polarity as the salient pole rotates [40]

Figure 2.4 illustrates various examples of three-phase PMFSM. A typical three-phase 12S-10P PMFSM is shown in Figure 2.4 (a), where the salient pole stator core consists of modular U-shaped laminated segments placed next to each other with circumferentially magnetised PMs placed in between them. The armature windings are reduced to form six armature windings as shown in Figure 2.4 (b), which results in less copper loss. The new E-core 12S-10P PMFSM is constructed as in Figure 2.4 (c). From this figure, half of the PM volume in Figure 2.4 (b) is removed, and the stator core is attached together to form E-Core stator. The new C-core 6S-10P PMFSM is developed as shown in Figure 2.4 (d), when the middle E-stator teeth is removed to enlarge the slot area. The rotor pole number is close to the stator pole number in the conventional

12S-10P PMFSM, while it is close to twice of the stator pole number in the E- and C-core PMFSM.

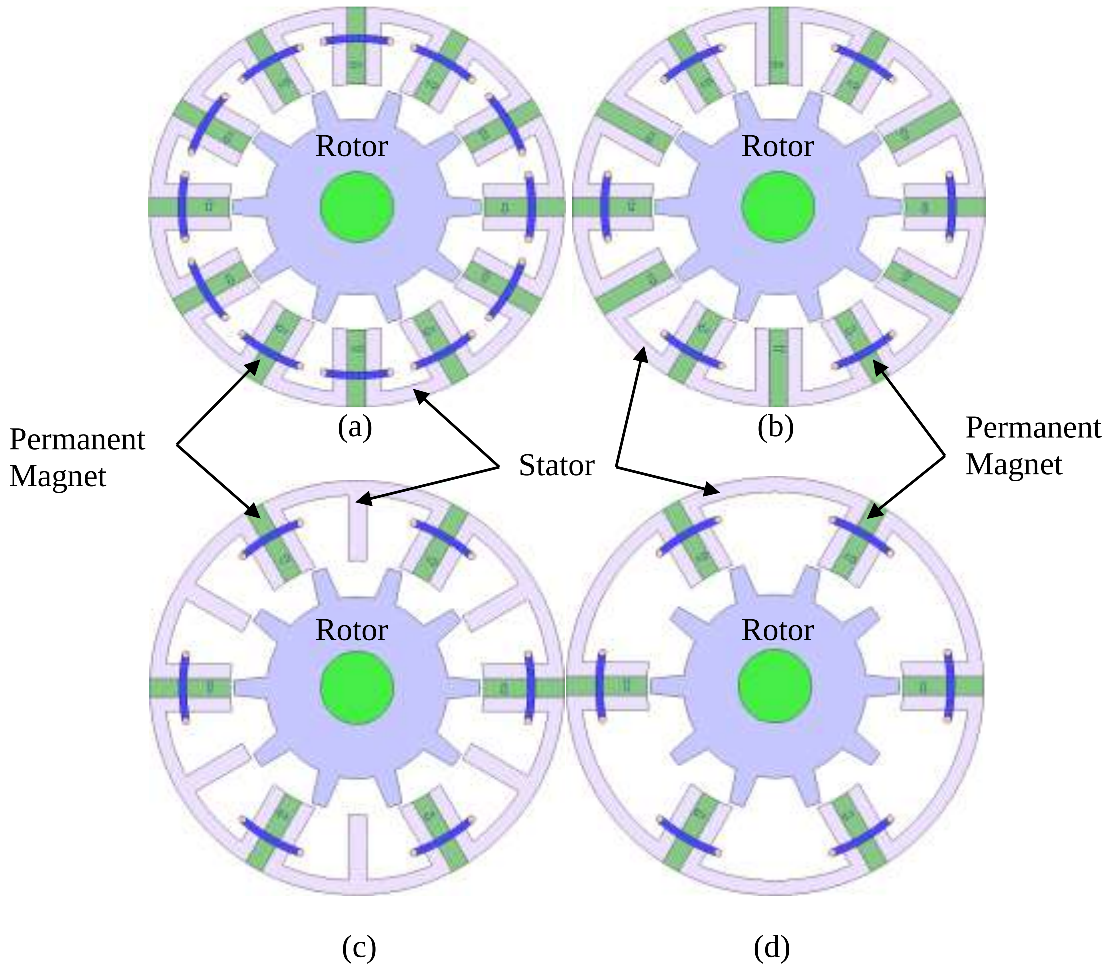

Figure 2.4: Examples of PMFSMs (a) 12S-10P PMFSM (b) Fault-tolerance PMFSM (c) E-core (d) C-core PMFSM [11]

2.4.2 Field Excitation Flux Switching Motor (FEFSM)

Field Excitation Flux Switching Motor (FEFSM) is distinct from PMFSM. Instead of PM it uses FE to generate flux. The stator is composed of laminated iron core, armature coils, and DC field excitation coil (FEC) as the only field mmf source. The rotor is made of only laminated iron core similar with SRM. The external DC source is applied to produce the magnetic field to make sure that current is flowing through to the winding. Even though the construction of FEFSM is not as simple as PMFSM because of the external DC source, the advantage of FEFSM is that it can control flux. Apart from that, there is no usage of rare-earth magnet resulting in reduced cost-up.

Figure 2.5 (a) illustrates an example of single-phase FEFSM with eight stator slots and four rotor poles, 8S-4P FEFSM, where the winding of FEC and AC alternate to each other. From this figure, the FEC is winded in four of the slots and fed with direct current to establish four pole magnetic fields. The other four slots contain an armature winding pitched over two stator teeth. Since the FEC is excited by unipolar current, it can be connected in parallel or in series with the DC-supply of power converter, which feeds the bipolar current into the armature winding. In addition, armature coil and FEC windings are overlapped to each other. From Figure 2.5 (b), it is clear that the structure of the three-phase inner-rotor FEFSMs have 24 stator teeth, 10 rotor poles, and alternate DC FEC and armature coil slot around the stator. Both designs have the potential to be low cost, and various flux capabilities suitable for low-torque performance and high-torque performance. In addition, the structure of the design is simple and easy to construct in the absence of PM.

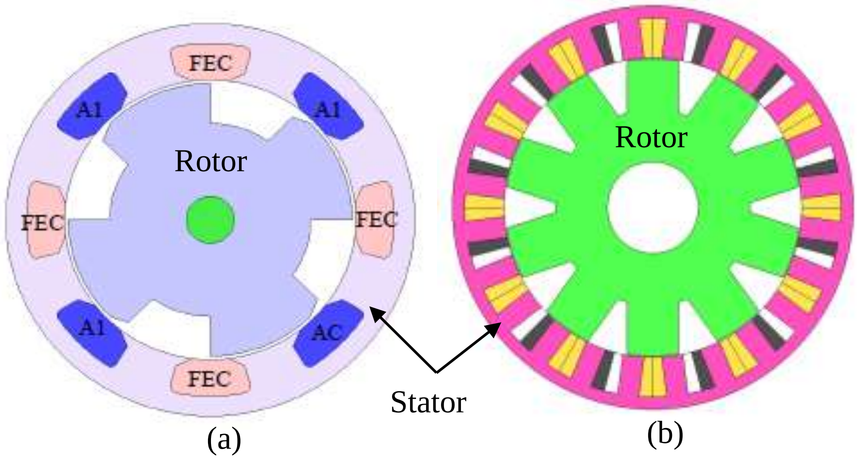

Figure 2.5: (a) Single phase 8S-4P FEFSM (b) Three Phase 12S-14P [17].

The operating principle of the FEFSM is illustrated in Figure 2.6. Figure 2.6 (a) and (b) show the direction of the FEC fluxes into the rotor while Figure 2.6 (c) and (d) illustrate the direction of FEC fluxes into the stator, which produces a complete cycle flux. Similar with PMFSM, the flux linkage of FEC switches its polarity by following the movement of the salient pole rotor, which creates the term “flux switching”. Each reversal of armature current shown by the transition between Figures 2.6 (a) and (b) causes the stator flux to switch between the alternate stator teeth [41].

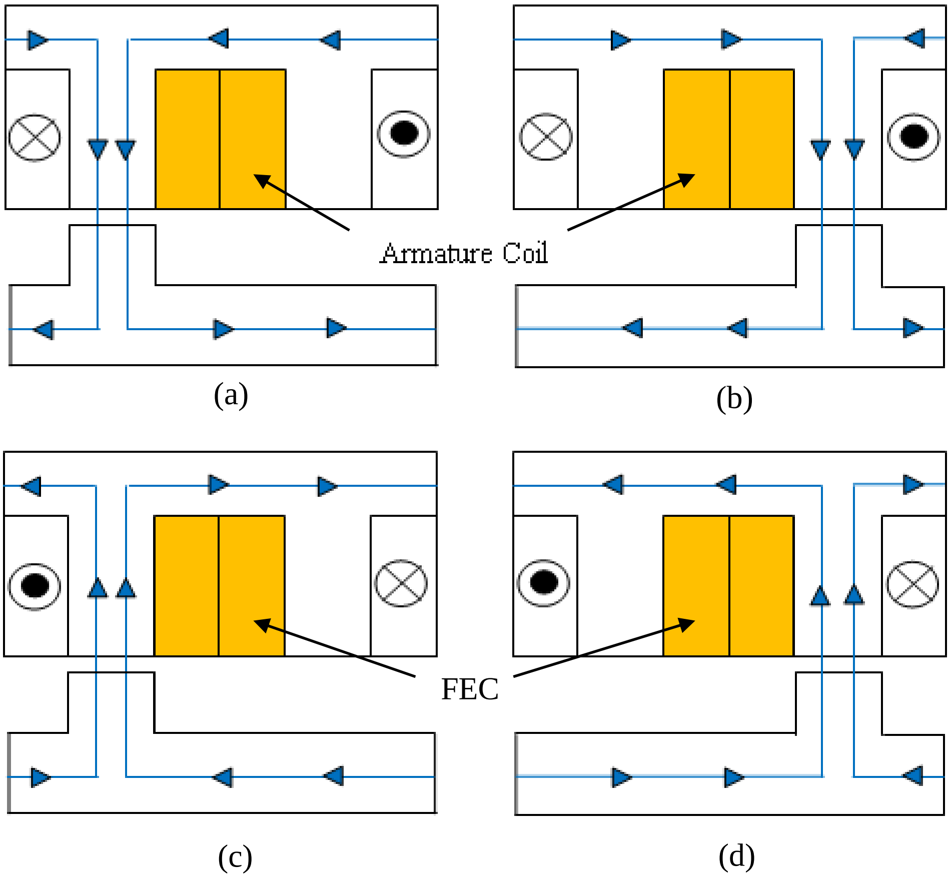

Figure 2.6: Principle operation of FEFSM (a) θ*e*=0° and (b) θ*e*=180° flux moves from stator to rotor (c) θ*e*=0° and (d) θ*e*=180° flux moves from rotor to stator [41]

2.4.3 Hybrid Excitation Flux Switching Motor (HEFSM)

Hybrid Excitation Flux Switching Motor (HEFSM) is the combination of PM and FE. HEFSM has significantly less magnet and higher torque density than those of a conventional PMFSM. To easily adjust the main flux, which is fixed in PMFSM, HEFSM were developed to improve the starting/low-speed torque and high-speed flux-weakening capabilities, which are required for HEV [42]. However, in addition to its inherent relatively low-torque density, it has a long end winding for the field windings, which overlaps the armature windings. Unfortunately, the foregoing hybrid-excited machines having magnets on the stator also suffer from these disadvantages. Firstly, the DC excitation field is in series with the field excited by magnets, which limits the flux-adjusting capability due to low permeability of magnets. Secondly, the flux path of DC excitation significantly reduces the main flux excited by magnets and even short circuits the magnet. In the meantime, torque density may be significantly reduced. In addition, the use of PM will add more cost because the price is expensive. Apart from that, HEFSM usually have complicated 3-D structure as a result of having difficulty to be analysed and manufactured.

Meanwhile, 12S-10P HEFSM with E-core stator is introduced as shown in Figure 2.7 (a). It has the same outer diameter with the outer-rotor from Figure 2.7 (b) while DC FEC is inserting in the middle teeth of E-core stator. In addition, it also yields non-overlapping between FEC and armature windings. From this figure, the winding connections and the magnetisetion directions of PMs and the volume of magnet in the E-core HEFSM is maintained similarly with the conventional E-core PMFSM.

In addition, the three-phase 12S-10P HEFSM with outer rotor configuration is also reported as shown in Figure 2.7 (b). The proposed machine has a very simple structure where all the components slots are in a rectangular shape and all coils are concentrated winding. From the figure, it is clear that the outer-rotor HEFSM has 24 stator teeth, 10 rotor poles with alternate DC FEC, PM and armature coil slot around the stator. In addition, it is expected that the machine offers a non-overlap winding between the DC FEC and armature coil to provide shorter end winding and hence contributing to reduced copper loss effect.

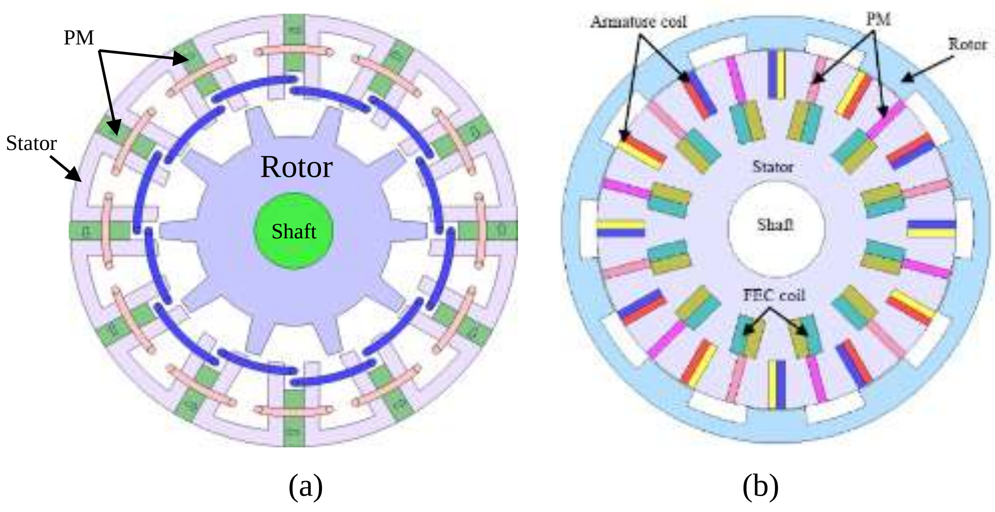

Figure 2.7 : Three-phase 12S-10P (a) inner rotor and inner FEC HEFSM (b) outer rotor HEFSM [43]

The operating principle of the proposed HEFSM is illustrated in Figure 2.8, where the red and blue line indicate the flux from PM and FEC, respectively. In Figure 2.8 (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 2.8 (c) and (d), where the FEC is in a reverse polarity, only the flux of PM flows into the rotor while the flux of FEC moves around the stator outer yoke, which results in less flux excitation [43].

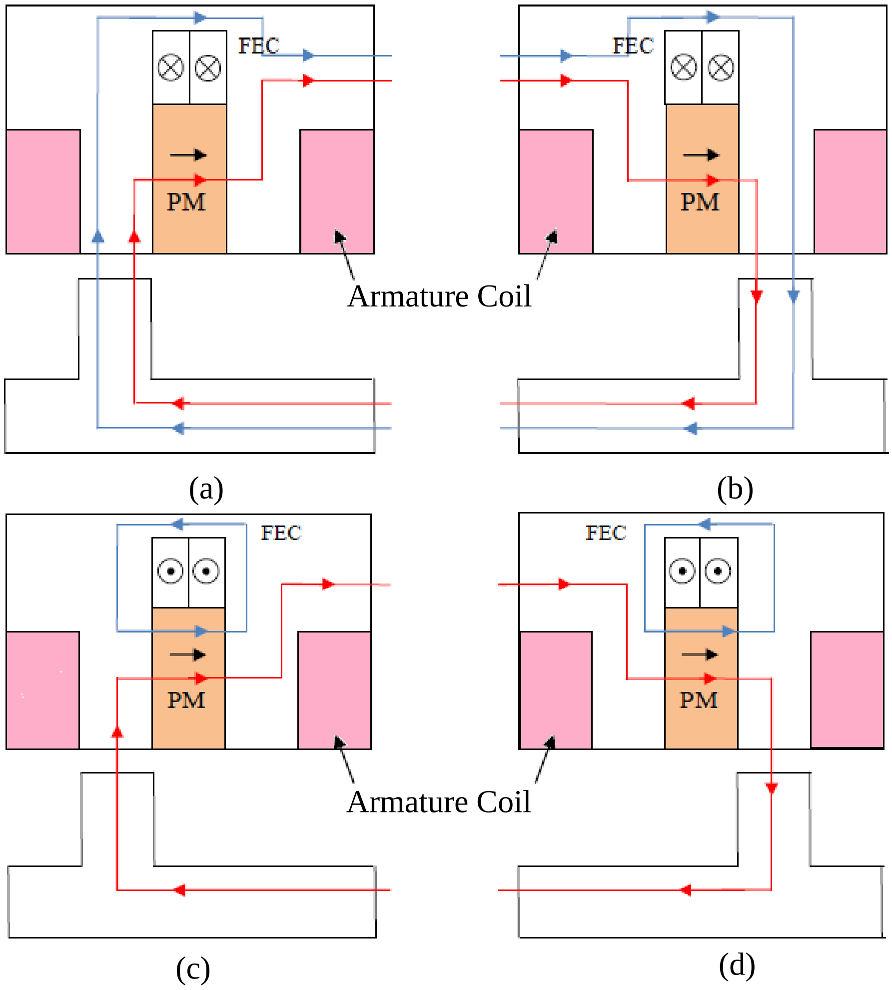

Figure 2.8: Principle operation of HEFSM (a) θ*e*=0° - more excitation (b) θ*e*=180° - more excitation (c) θ*e*=0° - less excitation (d) θ*e*=180° - less excitation [44]

2.5 Interior Permanent Magnet Synchronous Motor (IPMSM)

The history of the development of the IPM motors is linked to the advancement of high-energy PM materials over the past 100 years. In the 1950s, the most promising material was ferrite and barium ferrite magnets with a maximum energy product, BH_{max} of 1 to 4MGOe, which is a measure of magnet energy. In the late 1950s, aluminium nickel cobalt (AlNiCo) materials became the favoured PM with BH_{max} at around 5MGOe being developed by Merrill[45].

The usage of rare-earth magnets appeared in the 1960s. Binns, Barnard, and Jabber presented a series of flux-focused IPM motors using ferrite PM materials in the late 1970s [46], [47]. Samarium cobalt magnets became the popular metallic PM materials in 1970s with a BH_{max} at about 6MGOe. The latest quantum jump occurred in the early 1980s when neodymium boron iron (NdBFe) magnets with a BH_{max} at 14MGOe became commercially available. Rahman designed and built the first 45-kW high-efficiency IPM motor utilising NdBFe magnets in 1985 [48], [49]. Currently, NdBFe magnets with a BH_{max} at 60MGOe are manufactured and marketed by various magnet manufacturers. The critical properties of hard PMs for the IPM motors are very high coercive force (Hc), high residual magnetic flux density (Br), and high BH_{max} energy product. Of all the PM materials, NdBFe magnets are the most suitable for high-efficiency IPM motor drives.

An IPM motor consists of two components of the motor torque, namely the magnet torque and the reluctant torque. Hence, the IPM synchronous motor is a hybrid electrical machine. It is a well-known fact that the sum is always greater than parts. Two components of torques make up the total motor torque. Thus, an IPM motor develops more total torque than the reluctant torque or magnet torque alone. It is inherently more efficient than conventional induction or reluctance motors.

Figure 2.9 shows the example of IPMSM study done by Kazumasa Ando on the arrangement of the rare-earth PM in the outer-rotor magnet and the motor has a stator with concentrated winding. The armature terminals per phase are open and the rotor is rotated by an external force at a rated speed of 300 [rpm] under no load condition [6].

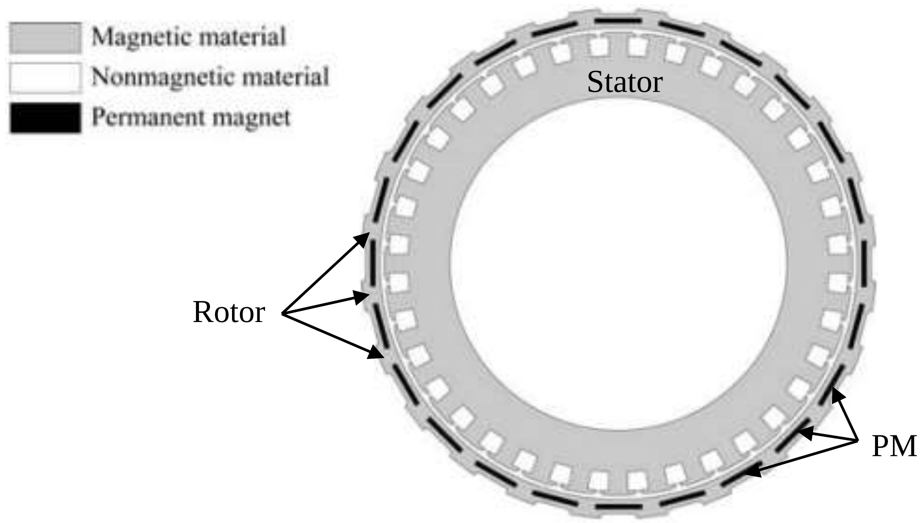

Figure 2.9 : Example of 36S-24P outer rotor IPMSM [6]

2.5.1 Applications of IPMSM

IPM synchronous motors are utilised in energy-efficient AC motor drives. Due to numerous advantage features such as high torque-to-current ratio, high power-to-weight ratio, high efficiency with high-power factor, and low noise and robustness, these modern highly energy efficient IPM synchronous motors are becoming widely accepted in many applications. IPMSM is intended to those that require high performances to meet the competitive motor drive market demand for quality products and improved services.

The reasons that these motors are now popular are due to the limitations of both the AC induction motor and conventional synchronous motor drives are overcome by singly fed IPM synchronous motors. One of the most successful applications of an IPM synchronous motor drive is its use for compressor pumps of modern energy-efficient air conditioners. The compressors are driven by high-efficiency IPM motors at around 10,000–12,000 r/min instead of the standard 2,500–3,500 r/min.

2.5.2 IPMSM Drawbacks

Based on the overview and classifications of various motors, PMFSM, FEFSM, and HEFSM have their own advantages and disadvantages. Among the three types of FSM, FEFSM is the best type to consider. This is because FEFSMs have many advantages over disadvantages as compared to both PMFSM and HEFSM. FEFSM does not adopt the usage of PM because PM is a rare-earth magnet that is costly for practical usage. IPMSM, which has been installed in existing HEV, has its drawbacks, in spite of their good performances as mentioned in [27]:

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

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

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

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

(v) The volume of PM used in IPMSM is very high, more than 1.0 kg, which increases the cost of the machine**.**

(vi) There could have windings at the rotor resulting poor robustness rotor structure for high-speed applications.

2.6 Research on FEFSM for HEV

Early examples of FEFSM, the three-phase 12S-10P, 12S-8P, and 12S-14P FEFSMs are developed as shown in Figure 2.10 (a), (b), and (c), respectively. The 12S-10P FEFSM in Figure 2.10 (a) is designed where the PM is removed from the stator and half of the armature coil slots in the upper layer are placed with the FEC windings as explained in [50]. The FEC-1 and FEC-2 are arranged with alternate DC current source polarity to produce two polarities of flux that can give much flux sources. However, since the isolated and unused stator teeth shown in red circle in Figure 2.10 (a) will

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