A NEW THREE-PHASE 6-SLOTS 10-POLES PERMANENT MAGNET FLUX SWITCHING MACHINE WITH INNER ROTOR CONFIGURATION

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MAHYUZIE BIN JENAL

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

Faculty of Electrical and Electronic Engineering
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JANUARY 2021

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged

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Dedicated to
my beloved family,
my siblings and my friends
who always encouraged me with their loves and prayers.

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ABSTRACT

Effective use of energy permits industrial and commercial facilities to cut down production costs, boost profits, and stay competitive. Also, the majority of electrical energy consumed in most industrial facilities is used to run electric motors. There has been a recent interest in flux switching motor (FSM) in which all flux sources are stalled in the stator that makes the rotor simple, robust, and brushless. Development of current research, particularly in conventional permanent magnet flux switching machine (PMFSM) has been with toothed rotor structures that employ permanent magnet at the stator that may manipulate the changes of paths for the stator teeth. Still this structure produces less torque and power. Hence, the use of multiple rotor structures has been developed, along with proposed PM configurations, which give significant gains. This research work focused on a new design of PMFSM employing alternate circumferential and radial flux (AlCiRaF) permanent magnet over various rotor poles configuration, optimization based on deterministic method and performance investigation through 2D-FEA. In this work, four topologies have been proposed, such as 6S-10P PMFSM with salient type of rotor (SalR), 6S-10P PMFSM with span rotor (SpR), 6S-8P AlCiRaF PMFSM with segmental rotor (SegR AlCIRaF) and 6S-10P AlCiRaF PMFSM with salient rotor (SalR AlCiRaF) are modeled and simulated using 2D-FEA JMAG v. 14.1 for the initial performance investigation. Since, 6S-10P SalR AlCiRaF has shown higher tendency to achieve better performances compared to conventional design, the model is then undergo further refinement through deterministic optimization method by shifting modeling free parameters in rotor and stator part. Finally, 6S-10P AlCiRaF has achieved better torque, power, speed ranges and efficiency compared with conventional 12Slot-10Pole PMFSM. Besides the optimized 6S-10P AlCiRaF has improved approximately 85.71% of maximum torque and 156% of maximum power than that of initial design machine proving their suitability towards efficient and reliable motors.

ABSTRAK

Penggunaan tenaga yang berkesan membolehkan kemudahan perindustrian dan komersil untuk mengurangkan kos pengeluaran, meningkatkan keuntungan dan kekal berdaya saing. Di samping itu, kebanyakan tenaga elektrik yang digunakan di kebanyakan kemudahan perindustrian digunakan untuk menjalankan motor elektrik. Baru-baru ini, terdapat minat yang baru-baru ini dalam mesin pensuisan fluks (FSM) di mana semua sumber fluks di pemegun telah menjadikan pemutar lebih mudah, teguh dan tanpa berus. Pembangunan penyelidikan semasa terutamanya dalam mesin konvensional pensuisan fluks magnet (PMFSM) dengan struktur pemutar bergigi yang menggunakan magnet kekal di pemegun yang boleh memanipulasi perubahan laluan fluks pada gigi pemegun tetapi struktur ini menghasilkan kurang tork dan kuasa. Oleh itu, penggunaan pelbagai struktur pemutar telah dibangunkan, bersama-sama dengan konfigurasi magnet kekal (PM) yang dicadangkan dimana memberi kelebihan yang ketara. Kerja penyelidikan ini tertumpu pada rekaan baru PMFSM dengan menggunakan magnet tetap lilitan dan aliran fluks (AlCiRaF) terhadap pelbagai konfigurasi kutub rotor, pengoptimuman berdasarkan kaedah deterministik dan penyiasatan prestasi melalui 2D-FEA. Terdapat empat topologi yang dicadangkan, 6S-10P PMFSM dengan jenis pemutar salient (SalR), 6S-10P PMFSM dengan rotor span (SpR), 6S-8P AlCiRaF PMFSM dengan rotor segmen (SegR AlCIRaF) dan 6S-10P AlCiRaF PMFSM pemutar (SalR AlCiRaF) dimodelkan dan disimulasikan menggunakan 2M-FEA JMAG v. 14.1 bagi penyiasatan prestasi awal. Oleh kerana 6S-10P SalR AlCiRaF telah menunjukkan kecenderungan yang lebih tinggi untuk mencapai prestasi yang lebih baik berbanding dengan reka bentuk konvensional, model itu kemudian menjalani penambahbaikan selanjutnya melalui kaedah pengoptimalan deterministik dengan mengubahsuai parameter bebas pemodelan di bahagian pemutar dan pemegun. Akhirnya, 6S-10P AlCiRaF telah mencapai tork, kuasa, julat kelajuan dan kecekapan yang lebih baik berbanding mesin konsional 12Slot-10Pole PMFSM. Di samping itu, 6S-10P AlCiRaF yang optimum telah meningkatkan kira-kira 85.71% tork maksimum dan 156% kuasa maksimum daripada

mesin reka bentuk awal membuktikan kesesuaian mereka terhadap motor yang cekap dan boleh dipercayai.

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A_g	-	Air gap
A_w	-	Area of wire
α	-	Filling factor
B	-	Magnetic field
E_B	-	Bottom end coil length
E_{ind}	-	The voltage induced in the turn of the coil
E_T	-	Top end coil length
e_k	-	Phase back-emf
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
H	-	Stack length
I_a	-	Armature coil current
I_e	-	Field excitation coil current
i_k	-	Phase current
J_a	-	Armature current density
J_e	-	Field current density
k	-	Phase designation
L	-	Length of 1 turn
L_k	-	Phase winding inductance
L_{si}	-	Circumference of the inner stator
m	-	Natural number
η	-	Efficiency
N	-	Number of turns of wire in coil
N_{cte}	-	Electrical angle of rotation for each period of cogging torque
N_{ctp}	-	Number of periods
N_e	-	Number of FE coils

N_r - Number of rotor poles
N_s - Number of stator slots
n_s - Rotational speed in revolution per minute
P - Instantaneous power
P_{ac} - Armature coil copper loss
P_c - Copper loss
P_{fec} - FEC copper loss
P_i - Iron loss
P_o - Output power
P_r - Rotor iron loss
P_s - Stator iron loss
R - Resistance
r_{ir} - Inner radius of the rotor
r_{or} - Outer radius of the rotor
r_{sbi} - Radius of stator back inner
r_{si} - Inner radius of the stator
r_{so} - Outer radius of the stator
S_e - FEC slot area
S_a - Armature coil slot area
t - Time
T_e - Electromagnetic torque
T_{rel} - Reluctance torque
T_{exc} - Excitation torque
w_r - Rotor tooth width
w_s - Stator tooth width
ω_r - Rotational speed in radian per second
θ - Electrical angular position of the rotor
θ_{seg} - Segmental rotor span
ρ - Copper resistivity
φ - Flux
Ψ_{exc} - Flux linkage due to field excitation
ABC - Artificial Bee Colony
ACW - Anti-clockwise

AFPMSM - Axial flux permanent magnet machine
AlCiRaF - Alternate circumferencial and radial Flux directions
ASMA - Artificial bee colony-strength Pareto and evolutionary algorithm
CAD - Computer aided design
CGA - Conjugate gradient algorithm
CNC - Computer numerical control
CW - Clockwise
DC - Direct current
DE - Differential evolution
DFDSM - Doubly fed dual stator motor
DOM - Deterministic optimization method
Dy - Dysprosium
EA - Evolutionary algorithm
EDA - Estimation of distribution algorithm
EV - Electric vehicle
FE - Field excitation
FEA - Finite element analysis
FEFSM - Field excitation flux switching motor
FEM - Finite element method
FEC - Field excitation coil
FSM - Flux switching motor
GA - Genetic algorithm
GBA - Gradient based algorithm
HCF - Highest common factor
HE - Hybrid excitation
HEFSM - Hybrid excitation flux switching motor
IM - Induction motor
IOA - Intelligent optimization algorithm
IPMSM - Interior permanent magnet synchronous motor
MOA - Multi-objective algorithm
Nd - Neodymium
NSGA - Non-dominated sorting genetic algorithm
PM - Permanent magnet
PMFSM - Permanent magnet flux switching motor

PMSG - Permanent magnet synchronous generator
PMSM - Permanent magnet synchronous motor
PSO - Particle swarm optimization
RS - Response surface
SalR - Salient Rotor
SpR - Spin rotor structure
SegR - Segmental rotor structure
SPEA - Strength Pareto evolutionary algorithm
SQP - Sequential quadratic programming
SRM - Switched reluctance motors
THD - Total harmonic distortion
TM - Taguchi method
TS - Tabu search
WA - Winding arrangements

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The world in the 21st century today saw how the issue of global warming is a major concern by the public. Therefore, many extensive studies have been carried out by certain parties to prove that this is not an isolated issue that needs to underestimate but instead to come out with series of factor findings, promising proposals, and feasible solutions [1-5]. As reported in [1-2], one of the major factors in worsening global warming is the emission of human-made greenhouse gases (GHGs). Where carbon dioxide (CO_2) is identified as one of the major GHG released into the atmosphere by the combustion of fossil fuel [3].

The conventional internal combustion engine (ICE) has been used in vehicles for personal transportation for more than 100 years already. Currently, demand for private vehicles are increasing due to the rapidly rising rates of the world population. Among the main problems related to critical increased use of private vehicles is emission, whereby this has been a significant contributor to global warming, which has become an acute issue that must be faced by everyone. As a result, the government and related agencies have come up with more stringent standards to curb the problem of emissions and fuel efficiency. To obtain a wide-range full-performance high-efficiency vehicle while eliminating pollutant emissions, the most workable solution at present is the electric vehicle (EV), which driven by battery-based electric motor [6]-[10].

Generally, there are multiples important steps and attention requirements to make a selection of electric motor for EV propulsion systems, and the automotive industry is still hunting for the most appropriate one. In this case, the key features are efficiency, reliability, and cost. The process of selecting the appropriate electric propulsion systems should be carried out at the system level. Mainly, the choice of electric-propulsion systems for EV depends on three factors; driver's expectation, vehicle design constraints, and energy source. With these considerations, the specific motor operating points are difficult to define [11]. Hence, selecting the most appropriate electric-propulsion system for the EV is always a challenging task. At present, the major type of electric motors for EVs is the Flux Switching Machine (FSM) which has recently become a accessible and attractive design of machine type due to its numerous advantages such as high torque density and efficiency [12-16].

In 1955, FSM was first introduced as a single-phase alternator by Rauch and Johnson, consisting an only permanent magnet as the single magnetic flux source [17]. FSM has been receiving significant attention afterward, especially in electric propulsion system application and meanwhile, the first three-phase system was later developed in 1997 by E. Hoang et al [18]. Firstly, the invented permanent magnet flux switching machine (PMFSM), which is a permanent magnet (PM) single-phase limited angle actuator, or more well known as Laws relay, with four stator slots and four rotor poles was developed. It is extended into a single-phase generator with four stator slots and four or six rotor poles. FSM comprises all flux sources in the stator. Besides the advantage of brushless machine type, FSM also has a single piece of iron rotor structure that is robust and applicable for high-speed applications [19]. Over the past ten years, many new FSM topologies have been developed for various applications, ranging from low-cost domestic appliances, automotive, wind power, aerospace, and others [20].

In general, FSM can be broken down into three major clusters namely permanent magnet flux switching motor [PMFSM], field excitation flux switching motor [FEFSM], and hybrid excitation flux switching motor [HEFSM]. Both PMFSM and FEFSM have only one single main excitation flux source, respectively induced by permanent magnet and field excitation coil [FEC], whereas both PM and FECs are being used to generate flux in HEFSM. On the other hand, the armature winding and permanent magnet are both stationary in PMFSM but magnetic flux linkage can be altered either positive or negative polarity depends on the position of the rotating part. The concept of FSM is actually involved changing the polarity of the flux linking the armature winding by the motion of the rotor [21]. Finally, the excitation flux produced by permanent magnet flows from stator to rotor and oppositely from the rotor to the stator to accomplish one complete cycle. Similarly, this particular operation and principle take place for the rest of FEFSM and HEFSM as well.

However, in FEFSM the excitation source used is FE, which has lower flux strengthening as compared to PMs and hence, causes the less production of torque density. Besides, due to the usage of FEC the copper losses and copper cost is increased. On the other hand HEFSM combines the both sources to produce the torque however, due the flux cancellation effects HEFSM has complexities to produce torque.

Therefore, this research mainly focuses on the PMFSM implementing inner rotor structure along with various directions of PMs.

1.2 Problem Statements

Figure 1.1 shows a conventional 12S-10P three-phase PMFSM in which stator core consists of modular U-shaped laminated segments arranged next to each other with PMs slotted in between them. For flux switching operation principles, the PM magnetization polarity is being reversed from one magnet to another [22-24]. Stator armature winding consists of concentrated coils and each coil being wound around the stator tooth formed by two adjacent laminated segments and a magnet and it is however, inherits the disadvantage of high PM volume. Hence, variety of PMFSM designs have been reported since then. To reduce the consumption of PM, the stator

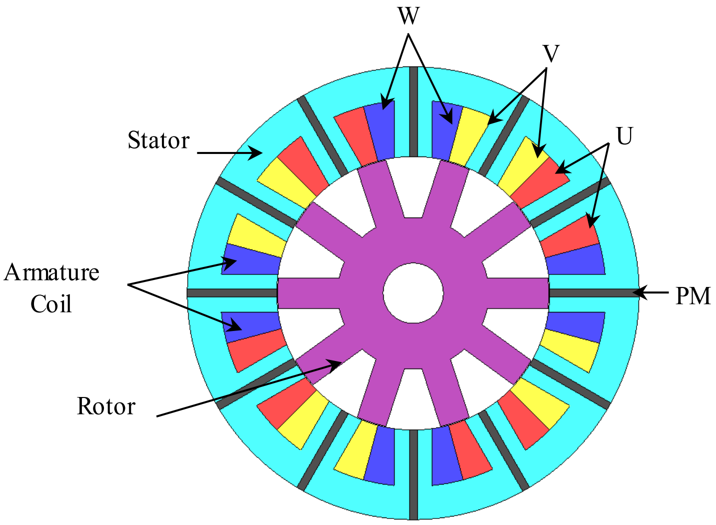


Figure 1.1: 12S-10P Conventional PMFSM Topologies

poles are replaced alternately by a simple stator tooth and therefore the new E-core is developed **[**24]. The stator core is merged to form an E-Core PMFSM stator and half of the PM volume in [18] is removed. The E-Core configuration is also presented in [25-27] with a combination arrangement between horizontal, and vertical of low-coercive force (LCF) magnets. The horizontal magnets are alternately attached to the stator teeth tips, and the vertical magnets remain identical as the conventional design. Moreover, the middle E-stator teeth can be removed to enlarge the slot area, and consequently, the new C-core PMFSM is introduced [28-29]. On top of these topologies, the main constraints are magnetic flux leakage at the outermost tips PM which limits the distribution of flux and also their separated stator from one segment to another that is hard to manufacture and assemble.

Therefore, to address all the shortcomings in existing PMFSMs including high PM volume, flux leakage, limited distribution of flux and manufacturing issues, new configurations of PMFSM implementing inner rotor structures are proposed in this research, such as 6S-10P salient rotor (SalR), 6S-8P spin rotor (SpR), 6S-8P segmental rotor (SegR) AlCiRaF, and 6S-10P SalR AlCiRaF are presented to execute comprehensive investigations over multiple design possibilities.

1.3 Objectives of the Study

The main objective of this research is to propose a new structure of a 3-phase permanent magnet flux switching machine using inner rotor configuration for light electric vehicles. In achieving the main objective, there are some specific objectives that must be fulfilled:

(i) To design and investigate the new structure model of three-phase PMFSM implementing inner rotor configurations for high torque density.

(ii) To analyse the performance of the proposed machines under various armature current densities for flux linkage, back-emf, cogging torque, torque speed characteristics, iron losses, copper losses of windings and efficiency.

(iii) To optimize the proposed inner rotor PMFSM and compare the simulation results with conventional PMFSM for optimum performance.

1.4 Scopes of the Research

Commercial Finite Element Analysis (FEA) package, JMAG-DESIGNER vers.14.1, released by Japan Research Institute (JRI) is used as a 2D-FEA solver throughout the study. Coil test analysis is performed for feasible topologies of inner and outer rotor PMFSM to confirm the operating principle. The limit of the current density is set to the maximum $30A_{rms}/mm^2$ for armature winding, and PM is solely used to be the magnetic flux source. The electromagnetic performance, including back emf, cogging torque and average torque has been analysed and compared using 2D-FEA. The torque-speed characteristics are evaluated by varying the armature phase angle, θ. The iron and copper losses are calculated based on 2D-FEA and formula, which assist in calculating the efficiency of proposed PMFSM. Finally, the deterministic optimization technique will be used to achieve better average torque and power for PMFSM.

1.5 Thesis Outlines

This thesis deals with the study of newly proposed PMFSM with various rotor configurations. This thesis is divided into five chapters, and the summary of each chapter is given below.

(a) Introduction:
The first chapter introduces the research, which includes the background of FSM and explanation regarding basic operating principle of FSM, problems of existing conventional PMFSM employing salient rotor and overlap windings, research objectives, research scopes and outlines of the thesis.

(b) Literature review:
Chapter two presents the overview and classifications of various electric motors used in light electric vehicles grouped under general electric motors and flux switching motors. Two kinds of electric vehicles were specified as hybrid, and all electric vehicles and two rotor types with configurations have been presented. The merits and demerits of general electric motors were highlighted and performance of various structures of FSM were comparedand optimization methods in electrical machines are discussed. From the findings, it was evident

that PMFSM offers free-loss excitation and viable for many applications, including automotive.

(c) Research Methodology:

Chapter three covers the project implementation has been divided into three stages including design various rotor pole of three-phase PMFSM, analysing performances of the proposed PMFSM and design optimization process. Initially, stage 1 is divided into two parts, namely geometry editor and JMAG Designer, while stage 2 is divided into two parts, which are no-load and load analysis by 2D FEA. Finally, stage 3 covers the optimization process for further design refinement as well as performances improvement.

(d) Result and Analysis:

Chapter four discusses the design and performance analyses of the initially proposed motor as well as the optimized design. This chapter is divided into two parts: result analysis of machine design with various rotor poles structures of three-phase PMFSM using a salient rotor, segmental rotor with non-overlap windings, analyse performances of the proposed PMFSM. Performances of different PMFSM designs in open-circuit condition were analysed and compared. The best performance of the proposed topology has been further refined and optimized where maximum load condition is applied in the second part.

(e) Conclusions and Future works:

Chapter five describes and concludes the research and suggestions for future works.

1.6 Chapter Summary

This chapter briefly describes the type of motors used on the existing low torque high-speed applications and identifying motor weaknesses. The 3-phase-phase the PMFSM using inner rotor configuration is introduced to overcome the drawbacks of previous 3-phase PMFSM. Also, the objectives, scopes, and outlines of the research are also briefly described in this chapter to explain the implementation of this research.

CHAPTER 2

ELECTRIC MACHINES: A REVIEW

2.1 Introduction

Electric motor (EM) receives an input electrical energy and transforms it into output mechanical energy. The device provides torque action and speed operation. As a result, the use of EM has brought significant advancement in all fields of technological developments and its application is found in low-cost domestic appliances, aerospace, and electric automotive [30].

Conventional vehicles such as scooters and motorcycles over the years have been equipped with an internal combustion engine (ICE) in which fuel oil is fired in a closed chamber for propulsion, has posed numerous economic imperatives. Due to the high cost of fuel oil, EMs have been developed and installed to complement the torque output provided by ICE, and it enhances fuel economy in hybrid electric vehicle and scooters. Meanwhile, choosing a suitable electrical motor for electrical applications is always a challenging task because certain kinds of machines are not very effective [31-33]. Motor types such as permanent magnet direct current (PMDC) motor, induction motor (IM), switched reluctance motor (SRM) and permanent magnet synchronous motor (PMSM) have been developed for automotive applications. Each of these motors has its own merits and demerits that need to be further improved [34].

PMDC is a synchronous magnetic motor that places PMs on the stator and uses an electromagnet with its coil wound on a soft magnetic core as the rotor. The working principle of PMDC motor is similar to the DC motor such that when a conductor carrying current comes inside a magnetic field, a mechanical force is experienced by the conductor, and the direction of this force is governed by Fleming’s left hand rule.

As in a PMDC motor, the armature is placed inside the magnetic field of permanent magnet, the armature rotates in the direction of the generated force. The rotational force is obtained between the stator PMs and the electromagnetic induction produced on the rotor by the current flowing while the brush magnet poles switch [35]. The structure is simple and durable, and do not have field windings in the stator. Meanwhile, PMDC motor has been prominent in electric vehicle application because its torque-speed characteristics are suitable for propulsion requirements and the control of the orthogonal disposition of field and armature magnetomotive force (mmf) is not difficult. Unfortunately, owing to thelow permeability of PMs, its armature reaction is usually lowered. Moreover, PMDC motors allow a considerable reduction in the stator slot area due to the efficient use of radial space. Figure 2.1 presents cross sections of PMDC motors.

IM consists of a stator frame made of laminations of silicon steel. The lamination is essential since a voltage is induced along the axial length of the steel as well as stator conductor. Construction of machines is rugged, low material cost, and its ability to operate in an unfriendly environment. The working principle of IM is based on the speed of the rotor at variance with the synchronous speed provided by the stator as there will be no relative speed and no induced-emf in the rotor. As a result, no current will flow, and torque will not be generated unless there is relative speed. Meanwhile, IM is used as a prospective candidate for electric applications due to its ruggedness, reliability, and low maintenance. In IM, there is an absence of PM

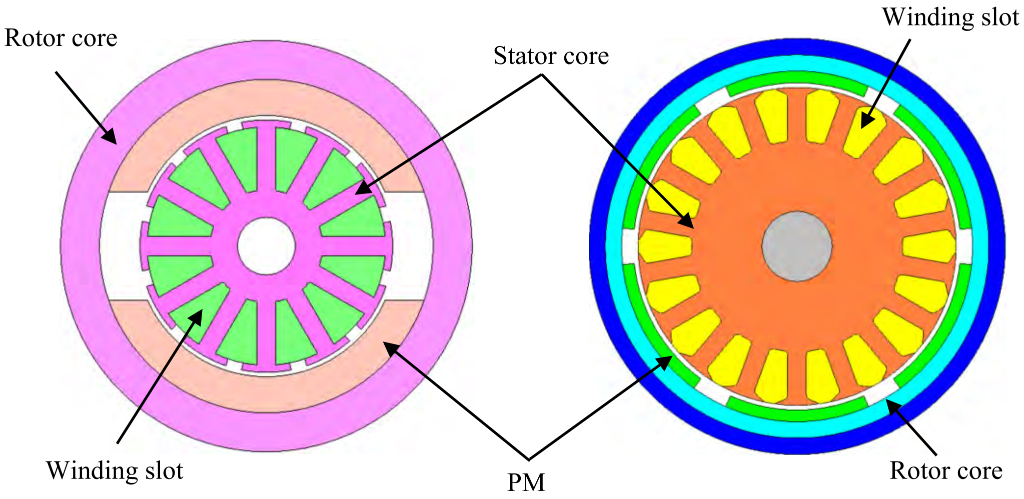


Figure 2.1: Cross sections of PMDC motors [35]

therefore, no disposition of permeability. Consequently, there is a presence of breakdown torque at a critical speed, which limits constant power operation and attempts to operate the motor at maximum current beyond the critical speed will create a breakdown of the motor. On the downsides, IM is characterised by low efficiency at low speed light regions of electric drives arising from the secondary loss. Furthermore, IM requires high electrical loading to realize high torque density and low power factor [36]. Cross sections of induction motors are shown in Figure 2.2.

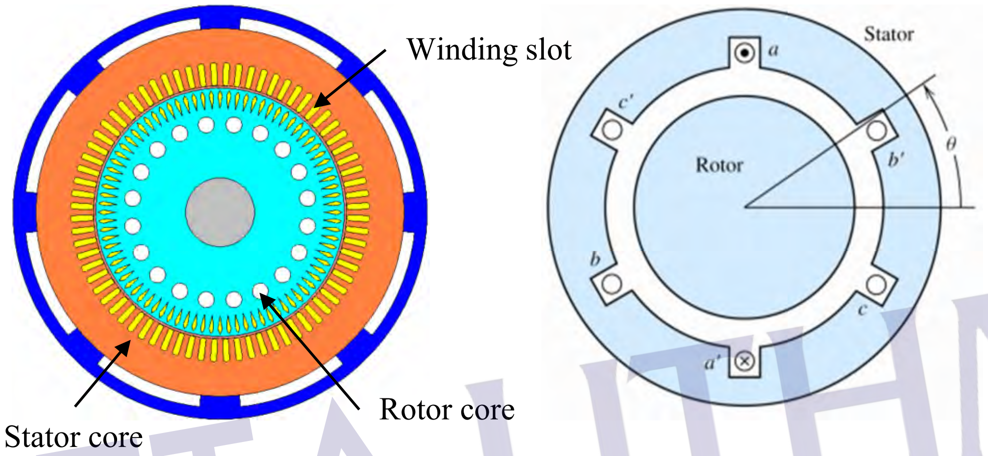


Figure 2.2: Cross sections of IMs [36]

The switched reluctance motor (SRM) like IM, does not utilize PM for excitation, the construction includes concentrated windings but no-windings on the rotor itself. SRM has the features of synchronous motor and tends themselves to the programming of their torque, and speed characteristics. The rotor position moves with the induction phase and the inductor changes periodically when the rotor rotates, which reflects the magnetic reluctance change. For automotive applications, SRM has compatibility of rotor with stator is an attractive motor due to its low-cost in mass production, low maintenance cost, high efficiency. Along with the ability to function in every harsh environment, easy to regulate, fault tolerant and suitable for high speed range [37- 39]. Conversely, SRM has low torque capability and generally noisy and can be used where controllability and shaft torque ripple is not critical. Meanwhile, the electromagnetic torque of SRM can be calculated as given in [40].

$$T_{em} = i\frac{dL}{d\theta} \tag{2.1}$$

Where T_{em} is electromagnetic torque, i is phase current pattern, and L is the inductance of winding.

P.J. Lawrenson (1967) happened to be the first person to champion the development of reluctance motors in the segmental rotor. In his work in [41], the single- phase 2S/2P SRM is derived from a conventional salient pole machine having replaced the central permeable cylinder of the salient pole rotor by a non-magnetic one whose magnetic circuit is shown in Figure 2.3 (a). The motor was experimentally validated excellent performance in terms of better power factor. Since then, many designs of SRM have been developed for various applications for automotive, as presented in Figure 2.3 (b) – (j).

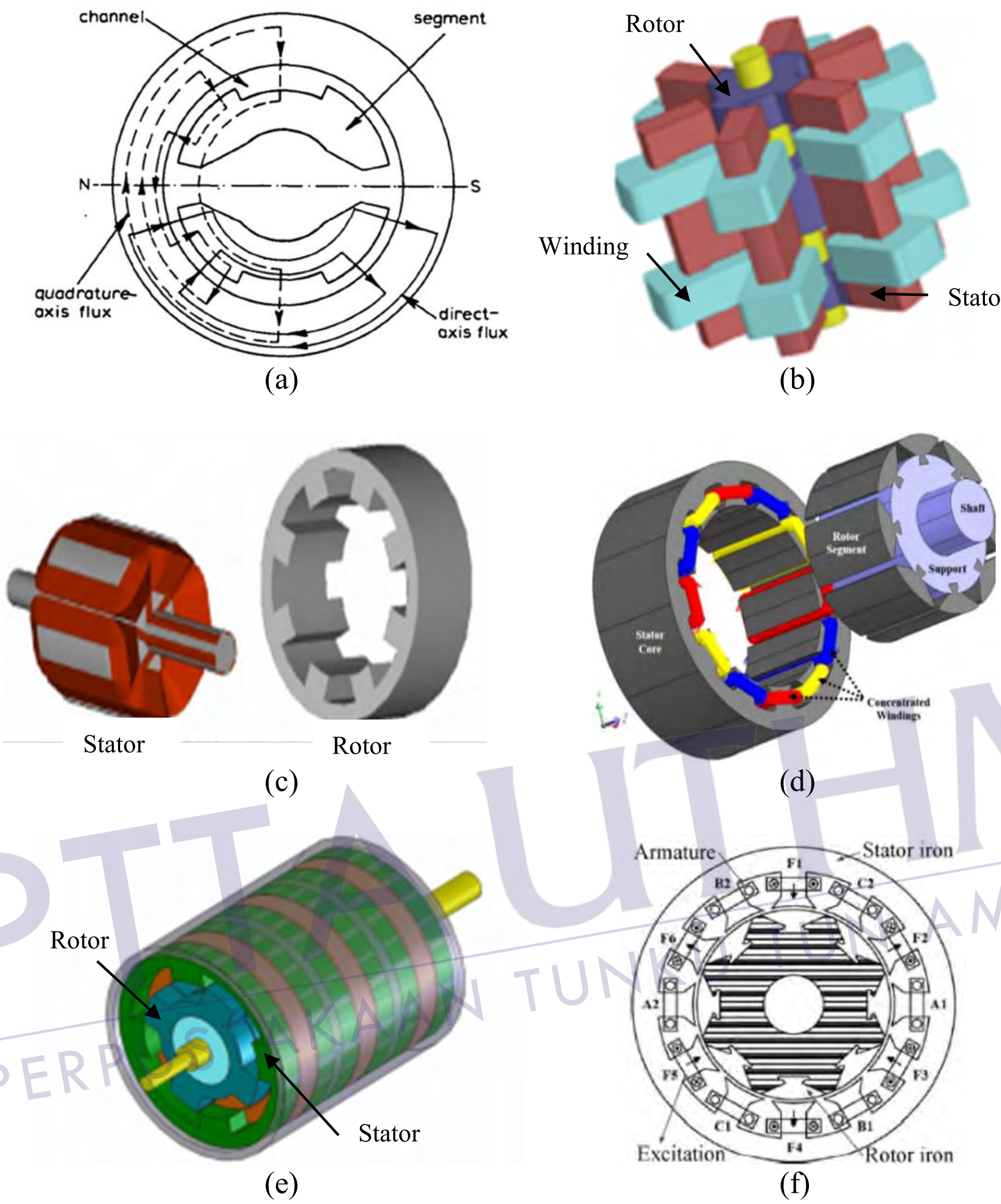
An example of SRM is the work of Ding, Linh & Yunpeng (2014) [42], which designed a modular motor comprising 6S/4P with E-core stator for high reliability automotive application. The motor is three-phase, composed of a segmented rotor which embraced hybrid and axial magnetic paths with cross-sections, as shown in Figure 2.3 (b).

However, in [43], the structure proposed 6S/8P SRM drives to reduce the total weight, volume, and increasing the efficiency of the scooter propulsion system. The design optimisation of the motor was conducted using Ansoft- Maxwell2D software, and compared by simulating different driving conditions of vehicle, the motor is shown in Figure 2.3 (c).

Another design is proposed by Kabir & Iqbal (2015) [44]. It is a 600 W three-phase 12S/8P SRM using standard inverters to improve machine torque and power densities, which is compared with conventional SRM at the same base-speed under the same excitation level as shown in Figure 2.3 (d).

Another design for high torque and low flux leakage is a new double layer per phase isolated SRM. The motor consists of different concentric independent windings, two layers of the stator poles, and three layers of the rotor pole. There are four types of SRM namely regular doubly cylindrical, disc type, multilayer, and linear motors, the proposed motor has longer pole length [45] as depicted in Figure 2.3 (e).

In another example by Lian, *et al* (2015) in [46] designed a 12S/8P SRM with fully pitched windings for high torque suitable for electric vehicle applications. The developed motor has the same diameter as referenced in [45-46]. However, the 2D-



(a) (b) (c) (d) (e) (f)

Figure 2.3: Cross sections of SRMs for various applications (a) 2S/2P SRM (b) 6S/4P SRM (c) 6S/8P SRM (d)12S/8P SRM (e) Double layer SRM (f) 12S/8P SRM [41]-[47]

FEA of the motor is based on ANSOFT. Figure 2.3 (f) shows the cross section of the motor.

Taking the advantages of the short end winding and fault tolerance associated with SRM, Lorand & Mircea (2012) in [47] designed a 16S/14P SRM for critical applications. Figure 2.4 (a) shows this motor with modular stator construction. Calculation of the mean diameter of motor measured at middle of the air-gap is shown in [48].

$$D_{g=}\left[\sqrt{\frac{P_{2N}.Q_S.k_a}{Q_R.\pi^2..kL.\frac{nN}{60}.B_{g\,\max}.(1-\frac{1}{K_{cv}}).A_s}}\right]^{\frac{1}{3}} \tag{2.2}$$

Where D_g is the distance of air-gap length, Q_S, Q_R are the stator/rotor pole numbers, k_a, k_L and are coefficients of the leakage factors chosen between 75-95%, P_{2N} is the rated power, *nN* is the rated speed, *Bgmax* is the air-gap flux density in aligned position

Another example is multi-layer SRM by Ferhat & Nurettin (2008) in [48] for torque ripple reduction, high starting torque and smooth torque performance capability [49]. The motor modified the three phase 6S/4P classical model for improved torque density. Construction of motor consists of two magnetically isolated components and each part is a layer as shown in Figure 2.4 (b).

While all the aforementioned designs are inner rotors for hybrid applications, outer-rotor configuration is for all-electric and direct drive application. Vandana & Bayon (2013) had taken a bold step to develop SRM in outer rotor configuration [50]. This three-phase motor consists of 12S/26P for high torque and high efficiency. The selection of higher number of rotor is aimed at lowering the speed of rotor and thereby reducing iron loss. Figure 2.4 (c) shows the design feature of 12S/26P SRM in outer rotor. The instantaneous torque *t* of the designed motor is expressed as (2.3):

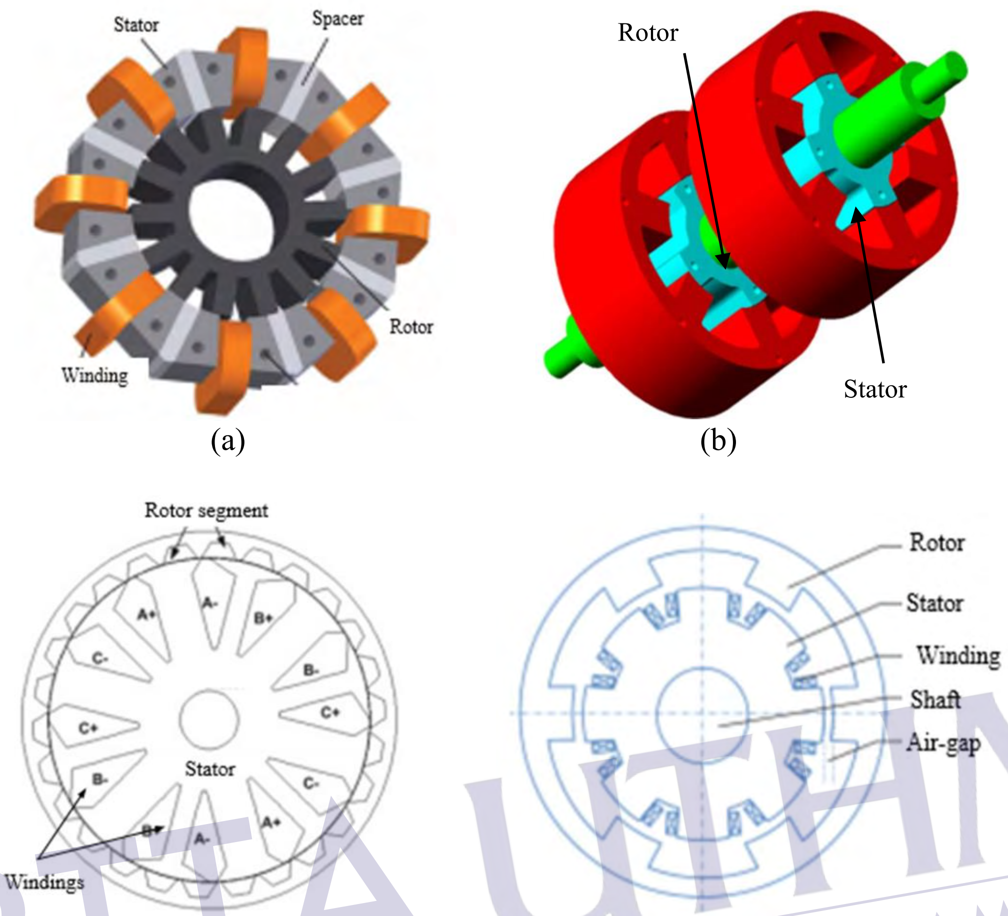
$$t = NI\frac{d\phi}{d\theta} \tag{2.3}$$

Where N is the number of turns, I is the peak phase current.

However, average torque T is given as:

$$T = mN_r NI\frac{\phi_a - \phi_u}{2\pi} = \frac{mN_r NI}{2\pi}\phi_a(1-\frac{\phi_u}{\phi_a}) \tag{2.4}$$

Where m is the number of phases, ϕ_a is the aligned flux, ϕ_u is leakage flux, N_r number of rotor segments.



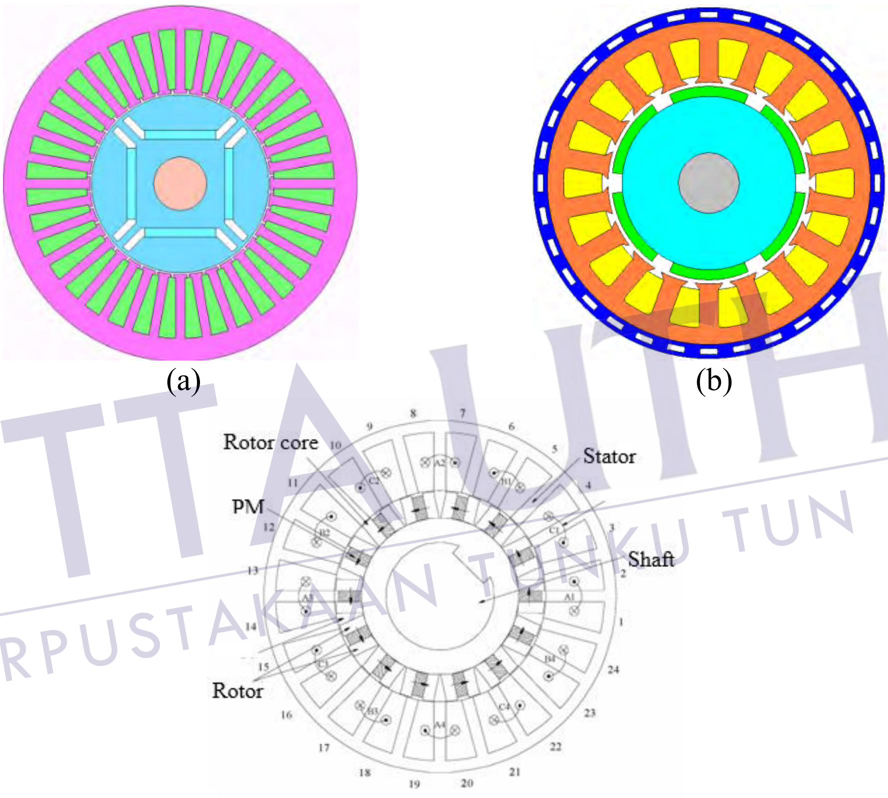
(a) (b)

(c) (d)

Figure 2.4: Cross sections of SRMs for various applications, (a) 16S/14P SRM (segmented stator), (b) 6S/4P SRM, (c) Double 12S/26P SRM (salient rotor), and (d) 8S/6P SRM (salient rotor) [48]-[50].

Another example in [51], outer rotor 8S/6P SRM is designed for high torque and to overcome the problem of noise and vibration which is always inherent disadvantage of SRM. It utilised the analytical Fourier fitting method for modelling which drastically reduced vibration to the minimal level. The cross section of the motor is shown in Figure 2.4 (d).

In other development for improved torque density, permanent magnet synchronous motors (PMSM) such as the interior permanent magnet synchronous motor (IPMSM), surface mounted PM and inserted PM, the field poles are created by using PM. This magnet is made of high permeability and high coercivity materials like neodymium -iron-boron. As the name implies, PM is implanted inside, placed on the surface or inserted in the salient rotor core, as shown in Figure 2.5. The design of IPMSM tends to be complex in that PMs are embedded right in the rotor core, and strength of rotor relies on the increase in the thickness ribs [36]. To overcome the challenges associated with IPMSM, various other designs have been proposed and fully discussed in [52-54]. Meanwhile, in all the mentioned motors, one thing is seen to be common is the location of active material on the rotor which adversely slows down the performance at high speed operation. Table 2.1 shows the performance of the general electric motors in terms of flux density, cogging torque, induced-emf average torque, and losses based on high level and low level. Furthermore, efficiency, weight and cost based on grade marks ranging from 1-5, where 5 represents the highest efficiency.



(a) (b) (c)

Figure 2.5: Cross sections of PMSMs with different PM orientations, (a) Interior PM, and (b) Surface mounted PM (c) Inserted PM [52-54]

Table 2.1: Performance comparison of general electric motors

Motor type	Flux density [Wb]	Induced back-emf [V]	Average torque [Nm]	Loss [W]	Advantages	Disadvantages
PMDC	High	High	High	High	Low torque ripple	Commutator
IM	Low	Low	Low	Low	Highly reliable	Not self-starting
SRM	Low	High	Low	High	Highly reliable	High torque ripple
SM	High	High	High	Low	Highly reliable	No start up torque

2.1.1 Electric motors in outer rotor configuration

Over the years, researchers had focussed on motor design in inner rotor configuration that limits the use of electric motors for other various applications. However, the application of outer rotor electric motor in the automotive application has assisted in the elimination of the mechanical transmission component in conventional vehicles, including a hybrid scooters. Therefore, motors in outer rotor design have advantages over inner rotor configuration due to the capability of delivering higher torque density and higher torque. In fact, the outer-rotor motor configuration offers benefits of space reduction and also achieves the high-to-weight ratio in application powered by stored electricity [56].

In [57], three-phase 24S/32P PMSM has been proposed for driving performance and dynamic characteristics. It consists of overlapping armature winding and surface mount permanent magnet synchronous machine (SMPMSM). The concept is applied to proper dynamic modelling, and control algorithm is required for performance and dynamic stability.

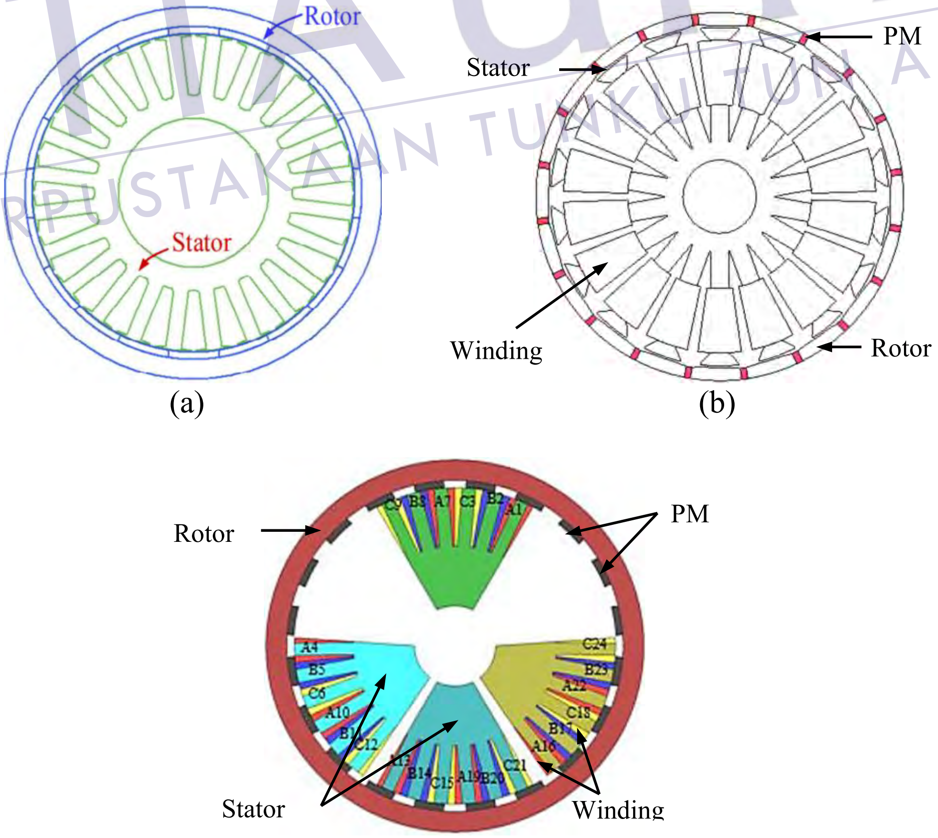
Accordingly, Kong Yong, Mingyao Lin, Da Xu, *et al.,* in [58], proposed a three-phase 24S/28P outer rotor permanent magnet synchronous motor (OR-PMSM) with amorphous stator core to improve the efficiency of OR-PMSM which is decided by magnetic loading while electric loading is proportional to the number of turns. Byeong-Mun, Ki-Chan & Jang-Young (2010) in [59] appeared to be the first to develop outer rotor type PMSM for an electric scooters as shown in Figure 2.5 (a). This motor consists of 24S/20P, a rotor mounted PM using concentrated armature winding and analysed using Green Motor Technologies. The electric loading of the motor is directly related to the flux density of PM and air-gap value. The electric loading, H is expressed as:

$$H = \frac{2mN_{ph}I}{\pi D} \tag{2.5}$$

Where m is the number of phases, N_{ph} is the number of turns in series per phase, I is the root mean square phase current (A), and D is the diameter of the air-gap (m). The larger the electric loading, the more copper, and the corresponding less iron in the motor.

Two more examples of three-phase OR-PMSMs for scooter applications are shown in Figure 2.6. Figure 2.6 (a) is a three-phase 24S/20P PMSM according to [60], was proposed to improve the efficiency of conventional OR-PMSM with a silicon steel core. It consists of amorphous state core and performance was validated using 2D finite element analysis, the three-phase 24S/20P PMSM is designed in which PMs have been inserted PM for high power performance as shown in Figure 2.6 (b). The two motors embrace different winding patterns and installed in the following electric scooters; Ujet electric scooter, Z-20 electric scooter, Aima electric scooters, Kingday electric scooters, Mobility electric scooter, and Terra motors, E-max, Vectrix and Zapino electric scooters and each operates with a different torque capability.

Furthermore, a segmented stator permanent magnet synchronous motor (SegStator-PMSM) has been developed for high torque and high power [29]. It consists of a four-cell stator embracing all-stator teeth armature winding with each segment, three phase as shown in Figure 2.6 (c). The proposed motor is fault tolerant while using surface mounted PM on a cylindrical rotor. Among many electric motors for scooters, the proposed motor has achieved high average torque, but its performance is constrained by mounting PM on the rotating rotor. Performance comparison between



(a) (b)

(c)

Figure 2.6: The cross sections of rotor PMs, (a) Surface mounted PMSM, (b) Inserted PMSM, and (c) SegStator-PMSM

the designs are presented in Table 2.2 in terms of armature winding, speed, torque density, power density, average torque and efficiency.

Table 2.2: Performance comparison of outer rotor PMSMs [60]

Motor type	Winding pattern	Speed [rev/min]	Torque [Nm]	Torque density [Nm/kg]	Power density [kW/kg]	Strength	Efficiency [%]
24S/20P PMSM	Concentrated	2000	45	2.95	0.15	Moderate	75
24S/20P PMSM	Distributed	2200	48	2.74	0.85	Moderate	67
24S/20P PMSM	All stator teeth	1900	110	3.8	1.03	Moderate	84

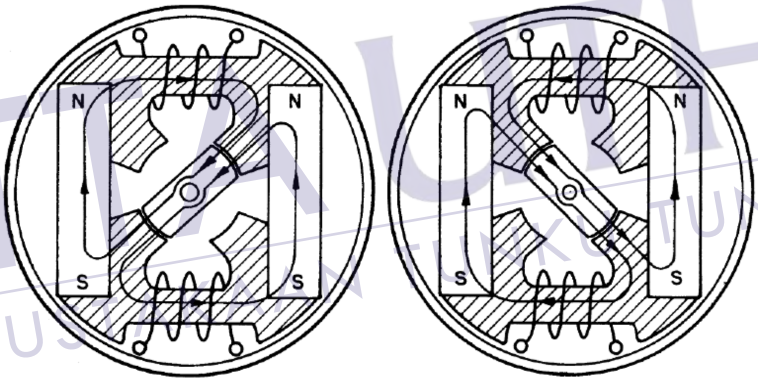
2.2 Flux switching motor (FSM)

Research and development have continued to improve on the performance of electric motors to overcome construction deficiency suitable for increased precision, less use of start-up energy, motor size, and less heat loss for effective output. FSM has been founded with good advantages in terms of construction, average torque, and high efficiency. FSM is an advanced form of the synchronous machine with unique characteristics. Unlike the machine types in which active materials are also located on the rotor, this machine locates all materials on the stator, leaving the rotating rotor to remain a single piece of iron. These features project it to be used for speed operation. Furthermore, FSM operates with double electrical frequency [61]-[62].

FSM has three internal types arising from excitation sources, namely, permanent magnet FSM, field excitation FSM and hybrid excitation FSM. While permanent magnet (PM) excitation flux is used in PMFSM, FEFSM uses field excitation coil that also needs external circuitry connection while HEFSM employs both PM and FE as main and secondary sources with external circuitry connections.

In the search for an electrical machine with improved performance, Rauch & Johnson in [63] developed the maiden flux switch alternator using PM source located on the stator with flux switching principle [64] later known as 'flux switching machine'. FSM is a synchronous machine in which the armature flux linkage changes with rotor position due to the change in permeance seen by the armature windings [41, 65]. This machine consists of a pair of stator windings, a dual set of the laminated yoke, and a pair of PMs were located on the stator, while the rotor is a two salient pole stack of lamination on the shaft as shown in Figure 2.7.

The flux paths shown by arrows in Figure 2.7 (a) indicate the flow of flux from left to right in both windings. When the rotor position is moved by a half-electrical cycle as in Figure 2.7 (b), the flux linkage had the same magnitude but the direction had been reversed as in Figure 2.7 (a). A complete reversal of flux was accompanied by each revolution of the rotor. Subsequently, the salient pole of the stationary part and stator operated in a conventional pulsating flux manner. PMFSM has a simple construction and requires no external field circuit connection, thus loss-free excitation. Based on the operating principle, the maiden design and development of PMFSM locates both PM flux source and armature winding on the stationary stator.

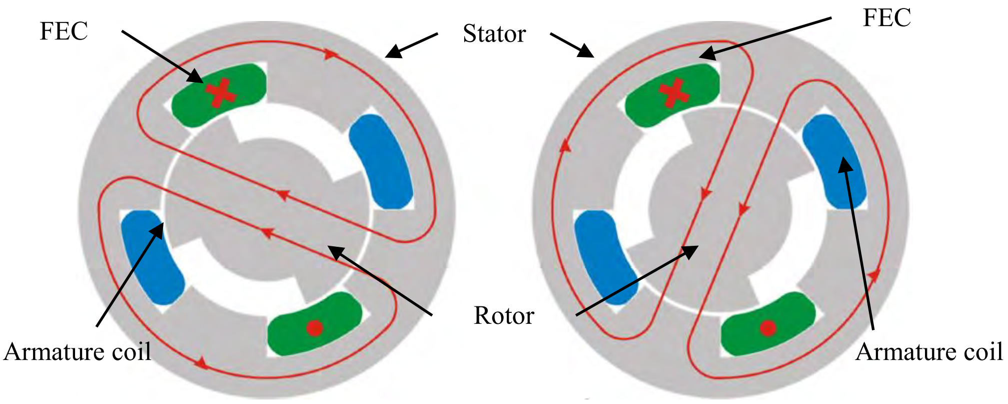


(a) (b)

Figure 2.7: Single-phase 4S/2P flux switch alternator (inner rotor) [63]

2.2.1 Field excitation flux switching motor (FEFSM)

FEFSM is a type of FSM which utilises field coil for excitation requiring external DC source. It is a high frequency alternator, proposed by Pollock & Wallace (1999) in [66]. They took the bold step to be the first to replace the PM of the machine with the appropriate field winding without altering the basic performance. The required resultant flux alignment was supplied by a field winding, and the scheme evolves from the inductor alternator 4S/2P with bipolar flux linkages and operating principle, as shown in Figure 2.8.



(a) (b)

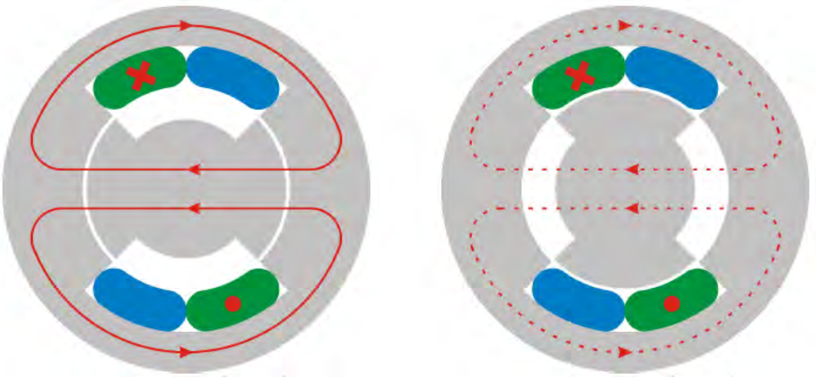
Figure 2.8: Basic 4S/2P configuration of FEFSM, (a) 1st alignment: +ve flux linkage, and (b) 2nd alignment: -ve flux linkage [66]

Meanwhile, with the emergence of alternate tooth stator, Dasgupta in [67] structurally mentioned the development of heteropolar FEFSM, which appeared simpler than all-pole of the same structure. This proposed motor has atime constant, more suitable for high frequency heating and other industrial applications. The basic configuration consists of slotted stator core laminations carrying both field and armature coils. For the 2S/2P FEFSM, the armature winding and field coils are being placed in the same armature slot or side by side while in 4S/4P design, the coils were arranged in an alternate winding pattern. The structures of both designs are shown in Figure 2.9 (a) and (b).

However, the innovation of FEFSM design, in contrast to PMFSM, is the deployment of DC field coil and armature winding to give the required flux direction for rotation [17, 68]. Accordingly, the feasibility of FEFSM design is reputable in applications requiring high power densities and a good level of durability [69].

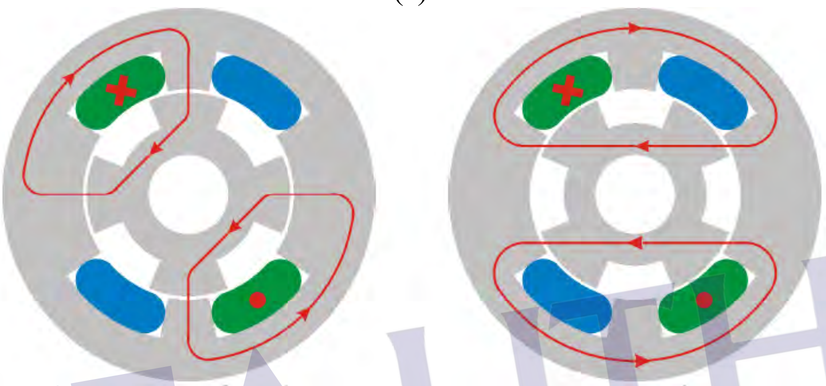
Furthermore, two single-phase topologies 8S/4P [70] and 12S/6P FEFSM [71-72] have been designed for industrial applications to reduce end-winding conductor materials as depicted in Figure 2.10. Each of them embraced overlapping winding between FEC and armature coil.

Meanwhile, single-phase FEFSMs have problems ranging from overlapping windings between FEC and armature coil, low starting torque, fixed direction, and large torque ripple. In another development, Lian et al., (2015) in [46] designed a three-



Aligned poles, maximum flux linkage Unaligned poles, minimum flux

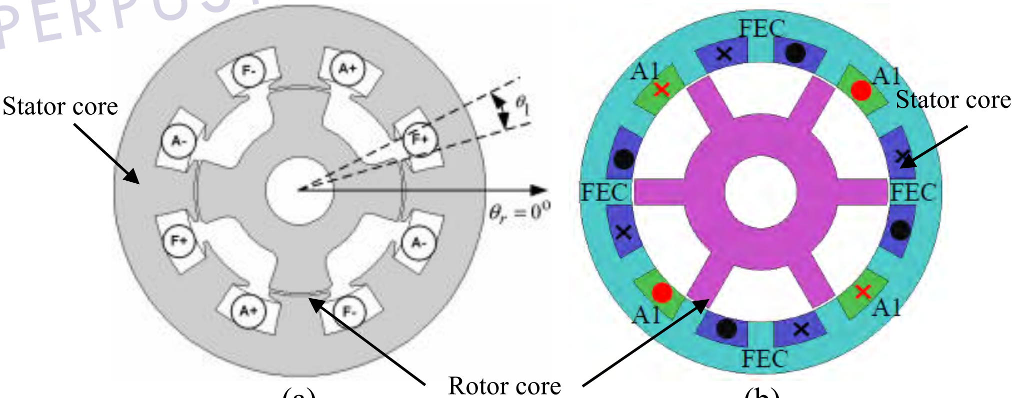
(a)



Aligned poles, minimum flux linkage Unaligned pole, minimum flux

(b)

Figure 2.9: Single - phase FEFSM (alternate poles), (a) 2S/2P common slot, unipolar flux linkage, and (b) 4S/4P alternate slot, unipolar flux linkage [67]



(a) (b)

Figure 2.10: Single-phase FEFSM, (a) 8S/4P, and (b) 12S/6P [70], [71]

phase 12S/8P FEFSM employing segmented rotor as depicted in Figure 2.11. It consists of two sets of armature windings per coil phase and the same number of field coil in alternate stator tooth winding, in clockwise direction. Segmented rotor, which

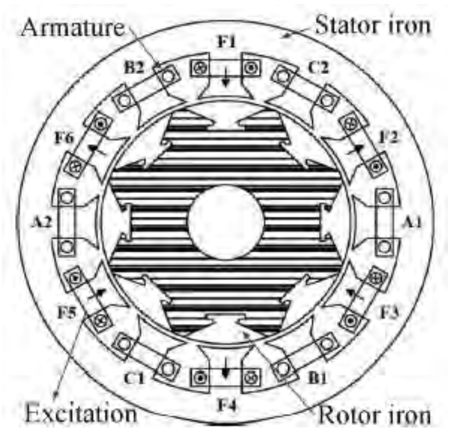


Figure 2.11: Three - phase 12S/8P FEFSM (segmented rotor) [45]

has the advantage of short flux path is used to control the saliency in synchronous reluctance machines, whose primary function in design is to provide a defined magnetic path for conveying the field flux to adjacent stator armature coils as the rotor rotates.

2.2.2 Hybrid excitation flux switching motor (HEFSM)

HEFSM combines both PM and FE as primary source and secondary source, the name came from its excitation sources. The PM flux source offers loss-free excitation while FE requires external circuitry connections.

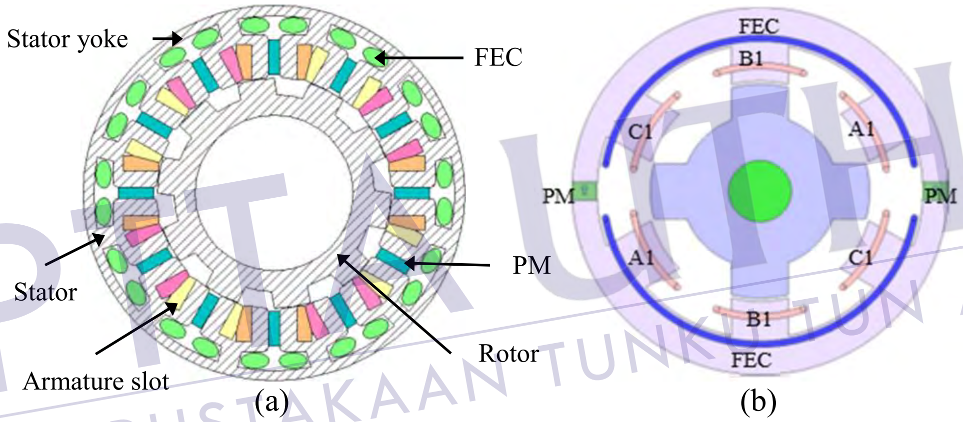
Hoang, Lecrivain & Gabsi (2007) in [73], appeared to be the first to design three-phase hybrid FSM topology. It consists of 12S/10P HEFSM and 12 PMs in a circumferential direction, with 12 FECs distributed uniformly in the midst of each armature coil. The motor was designed for high speed application and to operate in a hostile environment. Figure 2.12 (a) shows the proposed motor. So far, HEFSM has been investigated and found to have the potential of high torque, high power, variable flux capability and high efficiency for automotive application [74-75].

Similarly, another design is the work of Liao, Liang & Lipo (1992) in [76], developed 6S/4P HEFSM which consists of all-tooth armature winding, the overlapping field winding with less volume and number of PMs in the circumferential direction, shown in Figure 2.12 (b). In the configuration, PMs are located at the end of the stator core and an obvious long end DC winding. This is in series with the field excited by PM, and it limits the flux adjusting capability due to low permeability of the PM.

Another example is a three-phase 12S/10P HEFSM having a higher rotor pole number for high torque capability by Hua, *et al* in [77]. This design consists of U-shaped stator segments, and PMs are sandwiched between the stator segments leaving enough space for DC FEC, as shown in Figure 2.13. Meanwhile, effecting changes in a radial direction, the dimension of PM will affect the flux regulation capability of this HEFSM design structure.

Another design is an idealized 6S/10P HEFSM proposed in [78] consisting of an E-shaped stator core where both PM and armature coil in the conventional motor were sacrificed to reduce PM volume as shown in Figure 2.14(a).

Another example in [73] is 12S/10P HEFSM E-shaped stator core proposed by inserting DC field winding on the middle of E-core, torque density due to less volume



(a) (b)

Figure 2.12: Two examples of three-phase HEFSM, (a) 12S/10P HEFSM (2-layer stator core), and (b) 6S/4P HEFSM [76]

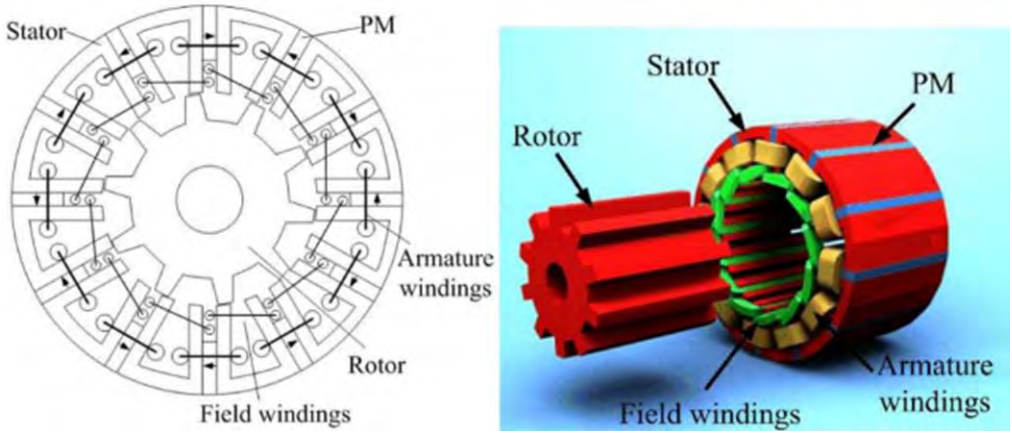
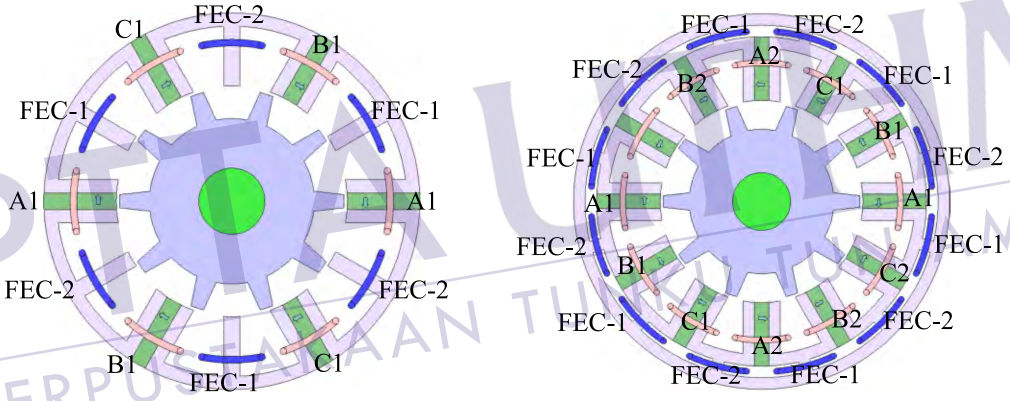


Figure 2.13: Three-phase 12S/10P HEFSM [77]

of PM may be significantly reduced as in Figure 2.14 (a). It has the same parameter dimensions with the HEFSM C-core.

Another example is three-phase 12S/10P HEFSM, which houses the FEC at the extremity of the stator core in [73]. However, the rear diameter of the motor is enlarged for the FEC winding. Furthermore, an idealized three-phase 12S/10P HEFSM for high torque and high power density application was proposed by Erwan (2012) [79]. It consists of concentrated armature winding and alternate PMs arranged in the circumferential direction. The cross sections of 12S/10P HEFSM are illustrated in Figure 2.15. Table 2.3 is a comparison of the FSMs. It is clear that PM has loss-free excitation, and short end winding. These are apparent advantages of PM motors over FE and HE motors. Using the advantages offered by PM, more details will be given on PMFSM in Section 2.2.3.



(a) (b)

Figure 2.14: Idealized 12S/10P HEFSMs, (a) 12S/10P HEFSM (E-core stator), and (b) 12S/10P HEFSM (2-layer stator core) [73], [79]

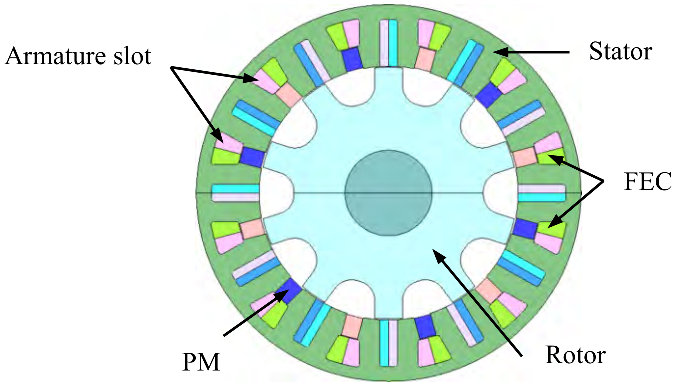


Figure 2.15: Cross sections of 12S/10P HEFSM [79]

Table 2.3: Flux excitation source comparison of FSMs

FEFSM	HEFSM	PMFSM
External DC source for excitation is required	External DC for source excitation is needed	No external DC source is needed
Simple construction	Complex stator structure	Simple construction
Presence of external circuitry connections	Presence of external circuitry connections	No external circuitry connections
Uses field coil	Uses PM and field coil	Uses PM flux source
Presence of winding loss	Presence of winding loss	No winding loss

2.2.3 Permanent magnet flux switching motor (PMFSM)

The maiden design of flux switch alternator from which the name flux switching machine is derived, used PM flux source excitation, thus PMFSM. The flux source is not subjected to the force arising from the body moving in a circular path. In PMFSM, the two active parts of armature winding and PM source are located on the static part of the stator for better heat transfer, the rotor is passive to allow for high rotational speed [15, 80]. In the principle of operation, FSM switches its polarity in the stator tooth by following the motion of the rotor, giving it an advantage over SRM, which operates using magnetic inductance change. PMFSM, based on the principle of flux switching, has attracted the researcher’s attention for continuous study. PM has additional advantages such as high torque density, good flux weakening capability, and high efficiency [81]. Meanwhile, various configurations of PMFSMs have been proposed to attain better performances in terms of high torque density, high torque, effective speed, and high constant power and efficiency for various automotive applications.

R. Deodhar *et al*. [82] had proposed a single-phase 2S/3P PMFSM for high-speed application as shown in Figure 2.16 (a). It has simple rotor construction, fully pitched and operating principle had been confirmed in [64]. Another example of single-phase PMFSM is 4S/8P designed for high-density application shown in Figure 2.16 (b) and documented in [83]. The proposed motor consists of concentrated winding with PM sandwiched between the stator teeth. Meanwhile, the synchronous motor does not have self-starting torque necessary to give it a defined direction. Therefore, PMFSM topologies with compact disc-type structures have been designed in [84].

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