DESIGN AND OPTIMISATION OF THREE-PHASE
SALIENT ROTOR WOUND FIELD FLUX
SWITCHING MOTOR

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DESIGN AND OPTIMISATION OF THREE-PHASE SALIENT ROTOR WOUND FIELD FLUX SWITCHING MOTOR

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This dissertation is dedicated to my parents, my wife, my brother, and sisters, who have always encouraged me with their love and prayers.
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ABSTRACT

Permanent magnet-free wound field flux switching machine (WFFSM) with a segmented rotor and non-overlapping windings is an attractive alternative for driving high torque density applications due to their low cost, high efficiency, high average torque and power. However, a rotor with segments makes the motor less robust and difficult to be assembled, while WFFSM with salient rotor and overlapping windings inherit high copper losses and less efficiency due to their long end-windings. This thesis deals with a novel structure of WFFSM employing a salient rotor with non-overlapping field and armature windings on the stator and a presentation of an unexcited rotor. The non-overlapping winding arrangement on the stator consumes less copper material, thus improves the efficiency. Moreover, the salient rotor structure with high mechanical strength is suitable for high-speed operation. The design restrictions and specifications of the proposed motor are keep similar as WFFSM with a segmented rotor. The J MAG-Designer ver.14.1 was used to verify the motor’s operating principle and performance characteristics. Three-phase configurations of WFFSM with non-overlap windings and salient rotor were studied, from the design features to performance analysis. For the three-phase operation, 11 topologies were feasible when employing a 12-tooth and 24-tooth stator. The subsequent optimisation work carried out using deterministic optimisation approach and Genetic Algorithm (GA) method to achieve the target average torque of 25.8 Nm and power of 6.49 kW. Designed and analysed by 2D and 3D finite element analysis (FEA), the optimised 12S-10P configuration had achieved high torque and power of 4.6% and 4.8% respectively, as compared to 12S-8P WFFSM with segmental rotor and non-overlapping windings. Moreover, the torque and power of the optimised design were also greater than 12S-8P WFFSM with salient rotor and overlapping windings. The 12S-14P topology had produced high average torque and power at low armature and field currents compared with all designs.
ABSTRAK

Mesin fluks beralih medan-belitan tanpa magnet kekal (WFFSM) dengan pemutar bersegsen dan belitan tidak bertindih adalah alternatif yang menarik terhadap aplikasi yang memerlukan ketumpatan tork yang tinggi. Ini disebabkan oleh kos yang rendah, kecekapan, tork dan kuasa purata yang tinggi. Walau bagaimanapun, pemutar bersegsen menjadikan motor kurang teguh serta sukar untuk dipasang, manakala, WFFSM dengan pemutar menonjol dan belitan bertindih menyebabkan kerugian pada penggunaan tembaga yang tinggi dan kecekapan yang kurang akibat daripada penghujung belitan yang panjang. Tesis ini berkaitan struktur baru WFFSM menggunakan pemutar menonjol yang mempunyai medan dan angker tanpa belitan bertindih pada pemegun dan pemutar yang tidak teruja. Susunan penggulungan tidak bertindih pada pemegun yang menggunakan kurang bahan tembaga, sekaligus mampu meningkatkan kecekapan. Selain itu, struktur pemutar menonjol dengan kekuatan mekanikal yang tinggi adalah sesuai untuk operasi mesin pada kelajuan tinggi. Had reka bentuk dan spesifikasi motor yang dicadangkan adalah masih sama seperti WFFSM dengan pemutar bersegsen. Perisian JMAG-Designer versi 14.1 telah digunakan untuk mengesahkan prinsip operasi dan prestasi motor. Konfigurasi tiga fasa WFFSM dengan belitan tidak bertindih dan pemutar menonjol telah dikaji, bermula dengan ciri-ciri rekabentuk sehingga analisis prestasi. Bagi operasi tiga fasa, 11 topologi telah dilaksanakan apabila menggunakan 12-gigi dan 24-gigi pemegun. Kerja-kerja pengoptimuman berikutnya dijalankan menggunakan pendekatan pengoptimuman berketentuan dan kaedah algoritma genetik (GA) untuk mencapai sasaran tork purata 25.8 Nm dan kuasa 6.49 kW. Setelah mesin direka dan dianalisis menggunakan kaedah 2D dan 3D analisis unsur terhingga (FEA), konfigurasi 12S-10P yang telah dioptimumkan telah mencapai tork yang tinggi dan kuasa sebanyak 4.6% dan 4.8% masing-masing, berbanding 12S-8P WFFSM dengan pemutar bersegsen dan belitan tidak bertindih. Selain itu, tork dan kuasa rekabentuk yang
dioptimumkan juga lebih tinggi daripada 12S-8P WFFSM dengan rotor menonjol dan belitan bertindih. Topologi 12S-14P telah menghasilkan tork purata dan kuasa yang tinggi pada arus angker dan arus medan yang rendah berbanding dengan keseluruhan rekabentuk motor.
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LIST OF SYMBOLS AND ABBREVIATIONS

$\eta$ - Efficiency
$\phi$ - Flux
$\Psi_{exc}$ - Flux linkage due to field excitation
$\theta$ - Electrical angular position of rotor
$\omega_r$ - Rotational speed
$\rho$ - Copper resistivity
$\alpha_{cog}$ - Electrical angle of rotation for each period of cogging torque
$\alpha_f$ - Filling factor
$B$ - Magnetic flux density
$F$ - Magnetomotive force
$f_e$ - Electrical frequency
$f_m$ - Mechanical rotation frequency
$i_a$ - Armature current
$i_d$ - d-axis current
$i_q$ - q-axis current
$i_f$ - Field current
$J_a$ - Armature current density
$J_e$ - Field current density
$k$ - Natural number
$\ell$ - Stack length
\( N \) - Number of turns
\( N_p \) - Number of periods
\( N_r \) - Number of rotor poles
\( N_s \) - Number of stator slots
\( P_c \) - Copper loss
\( P_i \) - Iron loss
\( P_{\text{mech}} \) - Mechanical power
\( q \) - Number of phases
\( R_u \) - Armature winding resistance per phase
\( \Re \) - Reluctance
\( S_a \) - Slot area
\( T_L \) - Load torque
CAD - Computer Aided Design
CNC - Computer Numerical Control
HE - Hybrid Excitation
EV - Electric Vehicle
FSM - Flux Switching Motor
FE - Field Excitation
FEC - Field Excitation Coil
FEA - Finite Element Analysis
GA - Genetic Algorithm
HEV - Hybrid Electric Vehicle
IPMSM - Interior Permanent Magnet Synchronous Motor
MEC - Magnetic Equivalent Circuit
SalRoN - Salient Rotor and Non-overlapping windings
SalRO - Salient Rotor and Overlapping windings
SegRoN - Segmental Rotor and Non-overlapping windings
WFFSM - Wound Field Flux Switching Machine
WFSSM - Wound Field Synchronous Machine
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<td>130</td>
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LIST OF PUBLICATIONS

Journals:


Proceedings:


LIST OF AWARDS

(i) **Gold Medal** in Seoul International Invention Fair, South Korea, [SIIF 2014]:
Erwan Sulaiman, Faisal Khan, Zhafir Aizat, Mubin Aizat, Sharifah Binti Saon, “Field Excitation Flux Switching Motor”.

(ii) **Silver Medal** at Malaysia Technology Expo, Kuala Lumpur, [MTE 2014]:
Erwan Sulaiman, Faisal Khan, Zarafi Ahmad, Zhafir Aizat “12Slot-10Pole Field Excitation Flux Switching Motor for Hybrid Electric Vehicles”.

(iii) **Bronze Medal** at Research & Innovation Festival, UTHM, [R & I 2013]:
Erwan Sulaiman, Faisal Khan, Zarafi Ahmad, Zhafir Aizat “Field Excitation Flux Switching Motor for Hybrid Electric Vehicles”.

(iv) **Silver Medal** at Malaysia Technology Expo, Kuala Lumpur, [MTE 2015]:

(v) **Copyright No. LY2015000027**, Erwan Sulaiman, Faisal Khan “Wound Field three-phase Flux Switching Motor with Non-overlap Winding and Salient Rotor for Hybrid Electric Vehicles”.

(vi) **Industrial Design No. 14-01422-0101**, Erwan Sulaiman, Faisal Khan “12Slot-10pole Wound Field three-phase Flux Switching Motor with Non-overlap Winding and Salient Rotor for Hybrid Electric Vehicle”.

(vii) **FRGS MOE Grant Vot. 1508**, “Characteristic investigations of a New Field Excitation Flux Switching Machine using Finite Element Analysis for Electric Vehicles”.

(viii) Participated in **3 minutes PhD thesis competition**, 2015 at national level held at Kuala Lumpur, organised by UTM.


(x) **3rd Prize** in postgraduate poster competition, 2015 at UTHM.
CHAPTER 1

INTRODUCTION

1.1 Research Background

Nowadays, a majority of industrial and domestic applications require more compact, more efficient, robust, light weight, and low-cost electric motors. As electric motors are the core of both industrial and domestic appliances, there is a pressing need for researchers to develop advanced electric motors. Latest research has made them literally invisible, installed within thousands of everyday products. They can be found in hybrid electric vehicles, fan, washing machine, air conditioners, vacuum cleaner, aerospace application, and rigid disc drives [1]. There are several classes of electric motors with standardised dimensions and characteristics. The development of the flux switching motor (FSM) [2], a new class of brushless motor is as recent as just over a decade ago. All the excitation sources of FSMs are located on the stator, providing simpler cooling options, while the rotor consists of only a single piece iron, neither magnet nor windings. FSMs are considered to be the most promising electric motor with high efficiency, easy thermal management, robust rotor structure, light weight, and cost-competitive. In addition, FSMs have been effectively applied to domestic and industrial applications [3-6].

FSM is a combination of a switched reluctance motor and an inductor alternator [7-8]. FSM can be categorised into three groups based on the method of excitation to stator: (1) Permanent Magnet (PMFSM), (2) Field Excitation (FEFSM), and (3) Hybrid Excitation (HEFSM). PM and field excitation coil (FEC) are the main sources of flux in PMFSM and FEFSM respectively while for HEFSM, both PM and FEC generate the flux [9-11]. Recently, the research work on PMFSM is dominated
by employing PM for primary excitation because of its high torque density, fault tolerance, and high efficiency [12]. However, with the growing demand of PM for electric motors, the annual consumption of rare-earth magnet has increased accordingly. This causes the prices of Neodymium (Nd) and Dysprosium (Dy) – an essential additive to provide the rare-earth magnet with high coercivity to rise markedly. Together, they raised serious concerns about soaring cost, security issues, and supply shortages. Hence, continuous research effort to develop electric motors with high power density and robust rotor structure without relying on rare-earth magnet is of the utmost importance [13]. It is desirable to completely replace the PM with FEC or diminish the usage of PM. In order to compete with existing PMFSM, some FEFSMs have been proposed for low cost and high-speed applications. The FEFSM has advantages of low cost, simple construction, magnet-less machine, and variable flux control capabilities suitable for various performances. The power density of FEFSM is higher, as the working temperature of FEFSM will not be limited by the working temperature of PMFSM [14-16]. The type of FSM that would be discussed within the context of this thesis is the FEFSM.

The three-phase FEFSM was simply designed by replacing the PM of 24Slot-10Pole PMFSM with FEC. However, the total flux generation was limited due to isolation of DC FEC and thus reducing the performances [14]. Moreover, the configuration of non-overlapping winding, instead of overlapping winding is preferred for machine design because of its advantages of short end windings and simple structure. If the slot pitch was close to the pole pitch, as in the case of similar numbers of slots and poles, then copper losses were reduced and high torque was produced in a non-overlapping winding, as discussed in [17-19]. To improve the drawbacks of FEFSM, 12S-8P FEFSM with segmental rotor was designed and experimentally tested [20]. Concentrated winding arrangement was used in this design, which gave shorter end windings of DC FEC and armature coil when compared with tooth rotor structure with distributed windings. This design had significant gains over other designs, as it utilised less conductor materials, thus improving the overall efficiency because of the reduction of copper loss. Examples of FEFSMs with single and dual polarity FEC were discussed in [21] and [5]. The advantages of FEFSM with single polarity FEC are low copper loss due to less volume of FEC, less leakage flux when compared with dual FEC windings. The field-weakening capability of FEFSM was improved using toroidal DC FEC [22].
1.2 Problem Statement

FEFSM was developed to overcome the drawbacks of rare earth materials used in PMFSM [13], demagnetisation problem [23], uncontrollable flux and less robust rotor owing to interior PM [24]. Various FEFSM structures are shown in Figure 1.1. There are certain problems in FEFSM such as segmental rotor that made the rotor less robust and cannot be used for high-speed application, as illustrated in Figure 1.1(a) [15], and overlapping armature and field windings that raised the copper losses in these machines [5], as shown in Figure 1.1(b). The segmented rotor FEFSM design has noteworthy gain over other designs as it consume less conductor.

Figure 1.1: Three-phase FEFSM, (a) 12S-8P FEFSM with segmental rotor, (b) 24S-10P FEFSM with dual FEC, (c) 24S-10P FEFSM with single FEC, (d) 12S-14P FEFSM with toroidal DC winding
materials, accordingly enhanced the overall efficiency due to reduction of copper loss. To deal with the problems, continuous research and development on electric machines with no PM, stable current, high synchronous speed and high efficiency would be very important.

FEFSM with single polarity FEC was discussed in [21], as shown in Figure 1.1(c). FEFSM with single polarity FEC has advantages of less copper loss when compared with dual FEC windings but the torque generation is limited. The field-weakening capability of FEFSM is improved using toroidal dc field winding, as shown in Figure 1.1(d). The proposed machine had limited torque generation, because the field flux produced by DC field conductors close to the outer surface of the stator went through the outside of the stator instead of the rotor, as well as high copper losses owing to overlapped armature and field windings.

1.3 Objectives of the Study

The main objective of this research is to develop a novel structure of salient rotor and non-overlapping windings (SalRoN) wound field flux switching motor (WFFSM) for high-speed applications. In achieving the main objective, there are some specific objectives that have to be fulfilled, which are:

(i) To design a novel SalRoN WFFSM and investigate its operating principle.

(ii) To investigate and analyse the significance of the new machine; the torque speed characteristics, mechanical stress of the rotor, torque density, power density, iron losses, copper losses of windings, and efficiency should be examined.

(iii) To optimise the SalRoN WFFSM for better average torque, output power, efficiency and torque-speed characteristics.

1.4 Scope

Commercial FEA package, JMAG-Designer ver.14.1, released by Japan Research Institute (JRI), was used as 2D-FEA solver for this design. 12 stator-slot topologies with the number of rotor poles limited to 5, 7, 8, 10, 14 and the 24 stator-slot topologies with number of rotor poles limited to 10, 14, 16, 20, 22 were investigated.
A coil test analysis was performed for feasible topologies of SalRoN WFFSM to confirm the operating principle. Assuming that only a water cooling system was employed, the limit of the current density was set to the maximum $30 \text{ A}_{\text{rms}}/\text{mm}^2$ for armature winding and $30 \text{ A/mm}^2$ for FEC, respectively. The electromagnetic performance, including back EMF, cogging torque, and average torque had been analysed and compared using 2D-FEA. The torque-speed characteristics were evaluated by varying the armature phase angle, $\theta$. The iron and copper losses were calculated based on 2D-FEA and formula, which assisted in calculating the efficiency of the proposed SalRoN WFFSM. The design restrictions, target specifications, and parameters of the proposed SalRoN WFFSM were based on the WFFSM employing a segmented rotor and non-overlapping windings. The outer diameter, the motor stack length, the shaft radius, and the air gap, having dimensions 150 mm, 70 mm, 24 mm and 0.3 mm, respectively, were kept constant. The electrical restrictions related with the inverter such as maximum 415V DC bus voltage was set similar as in the WFFSM with a segmented rotor and non-overlapping windings. The field current applied to SalRoN WFFSM was limited to 50 A.

1.5 Motivations for Research

For the past 10 years, the automotive, aerospace and shipbuilding industries have been working to design electric motors to improve the efficiency, torque and power as well as minimise the cost. In order to reduce the cost, rare earth material has been removed from the existing PM electric machines and their various characteristics are examined. Moreover, the efficiency is improved by employing non-overlapping windings that reduce the copper loss. The performance of WFFSM has been investigated, in response to economical and environmental pressures. As the capabilities of semiconductor devices and power converter grow, improvements in the performance of the WFFSM and considerations of new configurations are required.

The desktop workstation of modern technology has high processing power and speed and handles repetitive design problems with an ease not experienced before. JMAG tool with numeral analysis function for electric machine design using 2D and 3D-FEA are now routinely applied in design, analysis and optimisation of
machine dimensions. In the design and analysis of SalRoN WFFSM of this study, extensive use of 2D and 3D-FEA has been applied.

1.6 Contribution to Knowledge

The contributions of this research are as follows:

(i) Various structures of WFFSM have been reviewed and published.

(ii) It was explained that SalRoN WFFSM is particularly suitable for low cost and high-speed applications. A novel structure of light weight, more efficient, and robust rotor WFFSM was validated by 2D-FEA. This thesis elaborates the feasible topologies for three-phase SalRoN WFFSM.

(iii) Deterministic optimisation and GA methods were adopted to enhance the motor characteristics and compared with the existing designs of WFFSMs. The optimized design has achieved better characteristics than the existing designs and published.

(iv) Different methods were applied to reduce the cogging torque effect and the flux linkage were made sinusoidal by the rotor pole width variation.

(v) 3D-FEA modelling was examined for the precise analysis of SalRoN WFFSMs.

1.7 Thesis Organisation

This thesis deals with the design and optimisation of SalRoN WFFSM for high-speed applications. The thesis is divided into six chapters and the summary of each chapter is listed as follows:

(i) Chapter 1: Introduction

The first chapter explains the importance of magnetless high-speed electric machines and provides the broad context in which the motivation and research background with this work are embedded. The problems of current WFFSMs are highlighted and research objectives to solve the problems together with the major contributions are outlined in this chapter.
Chapter 2: Overview of Flux Switching Motors (FSMs)

The second chapter is a literature review that summarises the basic theory of flux switching and classification of FSM including the examples of PMFSM, FEFSM, and HEFSM. The structures, modelling techniques, and various characteristics of these FSMs are discussed in detail and compared. In the last section, a brief explanation is provided for structure review, flux linkage, cogging torque, average torque, efficiency, and analytical modelling of FEFSM.

Chapter 3: Design Methodology

The third chapter describes the design methodology of the proposed SalRoN WFFSM using commercial 2D-FEA, JMAG-Designer ver. 14.1, released by JSOL Corporation. Design process, coil arrangement test, and performance analysis are highlighted to investigate the performance of various topologies of SalRoN WFFSM. In a later section, the procedure of deterministic optimisation and GA methods are explained to treat various parameters of the machine and enhance its characteristics.

Chapter 4: Characteristics Investigation of the Proposed SalRoN WFFSM

In this chapter, the principle of flux switching by means of a salient rotor is portrayed with the help of elementary structure, and a calculating method of average torque is introduced for SalRoN WFFSM. Further design evaluations based on 2D-FEA and the changing pattern of 12S-8P SalRoN WFFSM characteristics with the variation of rotor pole width are presented in this chapter. Torque density, power density, and efficiency are calculated for the initial designs of SalRoN WFFSMs.

Chapter 5: Design Optimisation

Among the various slot combinations of SalRoN WFFSM discussed in chapter 4, the 12S-8P, 12S-10P, 12S-14P, and 24S-14P are optimised using deterministic optimisation and GA methods until the target performances are achieved. The results of the initial and optimised design that met the target performances are analysed and discussed. Various cogging torque reduction techniques are adopted to minimise the effect of cogging torque. Moreover, this chapter also explains 3D-FEA modelling of the design for precise analysis of axial flux.
(vi) Chapter 6: Conclusion and Future Works
The final chapter describes the major results and concludes the summary of the research as well as recommendations for future work.
CHAPTER 2

OVERVIEW OF FLUX SWITCHING MOTORS (FSMs)

This chapter reviews the types of rotating electric machine based on the principle of flux switching. It explains the flux switching mechanisms of different FSMs types, from the early concepts to the modern designs. The merits and demerits of various FSMs as well as numerous approaches to evaluate their performances are also highlighting. As the thesis is on WFFSMs that employ salient rotors, the last section provides more detail and significance of these machines.

2.1 Introduction

The variation of permeance seen by armature with respect to the rotor position changes the armature flux between the maximum (high state) and minimum (low state) values, and introduces a new term called ‘flux switching’. Electric machines that operate on this principle are called flux switching machines. The theoretical design of the inductor alternator based on flux switching has been known since 1940s [7], but the analytical approach appears to have come into use a decade later [25]. In [26], a PMFSM, i.e. PM single-phase limited angle actuator, or more well-known as Laws’ relay, has four stator slots and four rotor poles developed, while in [25] it was extended to a single-phase generator with four stator slots, and four or six rotor poles. Research work has been conducted on these machines for several years without using the term flux switching [27-30]. During the development of power electronics technology in the late 1990s, this term was used and investigated [31], [32]. Computer-aided design (CAD) tools with numeral analysis functions, normally Finite Element Analysis (FEA) using 2D or 3D, contributed a lot in design, analysis,
and optimisation of FSM. Over the past ten years or so, many novel FSM topologies have been developed for various applications, ranging from low-cost domestic appliances, automotive, wind power, and aerospace.

2.2 Operation and classification of the Flux Switching Machine

In the mid-1950s, the term ‘flux switching’ was used to explain an inductor alternator with bipolar armature flux linkages [25]. Figure 2.1(a) and (b) illustrate the simple mechanism of flux switching alternator. A pair of stator windings, a dual set of laminated yolks, and a pair of PMs were located on the stator, while the rotor was shown as a two salient pole stacks of laminations on the shaft. The flux paths shown by arrows in Figure 2.1(a) indicate the flow of the flux from left to right in both windings. When the rotor position was moved by a half-electrical cycle, as in Figure 2.1(b), the flux linkage had the same magnitude but the direction had been reversed as in Figure 2.1(a). A complete reversal of flux was attained by each revolution of the rotor. Consequently, the salient pole of the stationary part and stator operated in a conventional pulsating flux manner.

The PM of inductor alternator was replaced by appropriate field windings without altering the basic performance [32]. The required resultant flux orientation was supplied by a field winding with unipolar current and armature windings with single-phase current. The operation principle of flux switching motor without

Figure 2.1: A flux switching inductor alternator [25]
magnets could be described with the aid of Figure 2.2. Two possible aligned positions of the rotor were shown by cross-sectional views of the motor. Conventional cross and dot notations were used to indicate the path of current flow in the armature and field windings.

The combined resultant flux created by field and armature windings travelled in the northerly vertical direction; aligned the rotor with vertical stator poles, as illustrated in Figure 2.2(a). Considering Figure 2.2(b), the current in the armature winding was reversed for the next half cycle, while the field winding remained excited in the same direction causing the resultant flux to flow in the westerly direction, which tended to align the rotor with horizontal stator poles. Overlap armature and field windings has been caused copper losses in this motor and thus reduced the efficiency.

There are three classes of FSMs, namely permanent magnet FSM (PMFSM), field excitation FSM (FEFSM), and hybrid excitation FSM (HEFSM). They are broadly defined and differentiated by field flux source i.e PM or field winding and both PM and field winding, as illustrated in Figure 2.3.

![Figure 2.2: Basic operation principle with constant field winding excitation and single-phase armature current, (a) Armature flux linkage-positive and (b) Armature flux linkage-negative [32]](image-url)
2.3 Permanent Magnet Flux Switching Motor (PMFSM)

Over the past decade, PMFSM has been attracting a lot of research interest for various applications. The PMFSM has high magnet-consuming complex stator and is expensive to fabricate. Furthermore, the torque ripple must be considered, which is caused by severe magnetic saturation and irregular variation of winding inductances [33]. The PMFSM with PM embedded in the rotor has less robust structure and cannot be used for high-speed applications [24].

Due to the aforementioned demerits, the PMFSMs have not yet been practically applied in industrial and domestic applications.

2.3.1 Various Configurations of PMFSMs

Various configurations of PMFSMs have been proposed by researchers worldwide to attain better characteristics in terms of torque, speed, power, and efficiency. The development and various structures have been overviewed in [34]. For low energy axial fan applications, inexpensive ferrite magnet 4S-4P PMFSM was proposed as a cheap solution in [35]. Numerous PMFSM topologies [36-42] have been developed recently, they are mentioned as follows:

(i) Single-phase, three-phase, and multiphase PMFSMs [43], [34]
(ii) Fault tolerant PMFSMs [38]
(iii) Tabular PMFSM and Transverse flux PMFSM, [39], [40]
(iv) Outer and Inner rotor PMFSMs [41]
(v) PMFSMs with single-tooth or multi-tooth per pole [42]
(vi) E-core and C-core PMFSMs [44], [45]
(vii) Segmental rotor PMFSM [46]

Figure 2.4(a) illustrates a typical three-phase 12S-10P PMFSM, where the stator consists of concentrated armature winding, and each tooth is being wounded by a coil. A PM was placed between U-shaped laminated segments and the polarity of PM was reversed from one magnet to another [43]. For three-phase PMFSM, alternate poles wound windings were investigated to be fault tolerant, as shown in Figure 2.4(b) [38]. However, these PMFSMs had the disadvantage of high magnet volume. To reduce the volume of PM, a new structure of E-core PMFSM was developed by replacing the alternate wound pole with a simple stator tooth, as illustrated in Figure 2.4(c) [44]. Furthermore, to enhance the characteristics of E-core PMFSM, the stator tooth was removed to enlarge the slot area and as a result C-core PMFSM was developed, as illustrated in Figure 2.4(d). Additionally, the multi-tooth structure of PMFSM, discussed in [42], was utilised to improve the torque density and reduce magnet usage, as in Figure 2.4(e). A three-phase segmental rotor PMFSM was also reported, as shown in Figure 2.4(f). These kinds of machines have less robust structure, which need to be considered if they are applied for high-speed applications.

2.3.2 Modelling Techniques of PMFSMs

Numerous modelling techniques have been developed for PMFSMs and can be generally divided into two categories: analytical and numerical. The analytical approaches that are usually developed for specific geometry and topology are not as versatile as the numerical ones and might lead to inaccuracy. In contrast, the numerical measures, which are analysed with 2-D or 3-D FEA, present more precise evaluations for even complex geometry. However, 3-D FEA that involves several repetitive computations is extremely time-consuming for optimisation. Sizing-designing procedure of the PMFSM based on simplified analytical model is presented in [47]. Furthermore, the magnetic equivalent circuit (MEC) methods have been widely applied to model the PMFSM more accurately compared with analytical method. 12S-10P PMFSM was optimised and analysed by a new non-linear adaptive
Figure 2.4: Topologies of PMFSMs. (a) 12S-10P PMFSM with all poles wound, (b) PMFSM with alternate poles wound, (c) E-core PMFSM, (d) C-core PMFSM, (e) Multi-tooth PMFSM, (f) Segmental rotor PMFSM with all poles wound
lumped parameter MEC model [48]. Additionally, the PMFSM model was patched to analyse with iron bypass bridges [49]. For the radial flux PMFSM, 2-D FEA had been routinely employed as it could predict the performance with short computational time [50]. However, the 2-D FEA results are less precise due to assumption of zero axial flux.

### 2.4 Hybrid Excitation Flux Switching Motor (HEFSM)

A non-exhaustive review of HEFSM literature was presented in this section. HEFSMs are those that utilise two excitation flux sources: PM as well as FEC source, as shown in Figure 2.5 [51], [52]. HEFSMs have been investigated widely over many years and have the potential to provide high torque and power density, high efficiency, and variable flux capability [11], [53-55].

A 6S-4P HEFSM is shown in Figure 2.5(a), which consisted of armature winding, field winding, and PM, arranged in three layers in the stator [56]. However, this configuration had long end DC windings, which increased copper loss and reduces efficiency. A novel 12S-10P HEFSM was discussed in [53], in which the PM was placed between the stator segments leaving enough space for DC FEC, as depicted in Figure 2.5(b). The flux regulation capability of HEFSM can be controlled by adjusting the dimensions of PM in radial direction.

Non-overlapping armature and field windings were employed in the new structure of E-core HEFSM, as shown in Figure 2.5(c) [55]. The slot area for both FEC and armature winding were equal with same number of turns. Recently, three-phase E-core HEFSM with non-overlap windings and reduced PM size, as depicted in Figure 2.5(d), was analysed in [57]. The performance of E-Core HEFSM in terms of flux capability, torque, and power versus speed curve was also been examined. The proposed machine prides itself on the merits of lower cost and less copper.

The aforementioned HEFSMs with active components on the stator suffered from these disadvantages:

(i) Both the PM and FEC were in series with each other in Figure 2.5(a), which limited the flux-adjusting capacity owing to low permeability of PM.

(ii) The main flux generated by PM for maximum torque production was reduced by the flux path of DC FEC, Figure 2.5(b).
(iii) In Figures 2.5(b), (c), and (d), the PM was placed at the outer surface on the stator. Hence, the flux of PM acted as a leakage flux and had no involvement in torque generation.

(iv) The HEFSM was also difficult to manufacture due to segmented stator core, Figure 2.5(b) and (c).

(v) Torque density might be reduced because of less PM volume, Figure 2.5(d).

Figure 2.5: HEFSM examples, (a) 6S-4P HEFSM, (b) Three-phase 12S-10P HEFSM, (c) 12S-10P E-core HEFSM and (d) 6S-8Pole E-core HEFSM
2.5 Field Excitation Flux Switching Motor (FEFSM)

The quest for low-cost, high efficiency and simple configuration electric machines is an ongoing process. As the annual consumption and the cost of rare-earth material have increased over the past decade, the prices of Neodymium (Nd) and Dysprosium (Dy) used in PMFSM and HEFSM rise markedly which creates problems of supply shortages and security issues. To overcome this issue, the excitation on the stator of conventional PMFSM can be easily replaced by DC FEC to form field excitation flux switching motor (FEFSM). In other words, the FEFSM is a form of salient-rotor reluctance machine with a new topology. The concept of the FEFSM involves changing the polarity of the flux linking with the armature winding, with respect to the rotor position. The FEFSM has advantages of low cost, simple construction, magnet-less machine, and variable flux control capabilities suitable for various performances when compared with others FSMs. Many topologies of FEFSM have been studied and documented [1], [5], [15], [20], [21], [32], [58-61].

2.5.1 Structure review of FEFSM

Early examples of single-phase 4S-2P FEFSM that employ a DC FEC on the stator, a toothed-rotor structure, and fully-pitched windings on the stator were discussed [59]. Both the armature and field windings were placed in the stator, which overlapped each other and produced high copper losses. This design is practically used in various applications that require high power densities [60]. Single-phase AC and DC were applied to armature and field winding of this machine, respectively. The maximum flux interaction required for the rotation of rotor was supplied by armature coil at zero rotor position and the torque was produced by the variable mutual inductance of windings. The single-phase FEFSM can be considered as a simple machine that required two powered electronic controllers for armature and DC FEC. The main advantages of this design are low cost for high volume applications and precise control of position, torque, and speed.

Another example of FEFSM is depicted in Figure 2.6(a) with eight stator slots (four slots for armature coil and four for FEC) and four rotor poles. The design specifications and operation of 8S-4P FEFSM were explained in [61]. When
compared with induction machine, the FEFSM had achieved high torque and efficiency but the main problems concerned with this design are low starting torque, high torque ripples, overlapped windings, and fixed rotating direction. Two single-phase FEFSMs topologies with DC field and AC armature windings with the same coil-pitch of two slot-pitches and different coil-pitches of one and three slot-pitches respectively were discussed [6]. It is shown that the iron loss of FEFSM had been reduced and thus increased the efficiency. These machines shared the same operating principle as discussed in [61], but 12S-6P explained in [6] had much shorter end windings, and therefore, much better copper usage efficiency. These topologies had problems of overlap windings and high copper losses. The structure of single-phase

Figure 2.6: Single-phase FEFSMs, (a) Single-phase 8S-4P FEFSM, (b) single-phase 12S-6P FEFSM with salient rotor, (c) single-phase 8S-8P FEFSM with overlapping windings, (d) single-phase 12S-6P FEFSM with segmental rotor
FEFSM is illustrated in Figure 2.6(b). The performance analysis of single-phase 8S-8P FEFSM, depicted in Figure 2.6(c), was discussed in [62]. The proposed motor has high cogging torque and overlap armature and field windings which made it unsuitable to be applied for any electrical equipment. A single-phase 12S-6P FEFSM for high density air conditioner with segmental rotor was designed and discussed in [63]. The proposed motor had less copper losses due to non-overlap armature and field windings as shown in Figure 2.6(d). Although 12S-6P had high average power, the rotor was not robust due to segments, hence could not be used for high-speed applications.

The PM of 24S-10P PMFSM was replaced by FEC to design a three-phase FEFSM, as illustrated in Figure 2.7(a). The total flux generation was limited due to the isolation of DC FEC and thus reducing the performances [14]. To improve the drawbacks of FEFSM, 12S-8P FEFSM with segmental rotor was designed and experimentally tested [20]. Concentrated winding arrangement was used in this design, which gave shorter end windings of DC FEC and armature coil when compared with the tooth rotor structure with distributed windings. This design had significant gains over other designs as it utilised less conductor materials, thus improving the overall efficiency due to the reduction of copper loss. FEFSMs with single and dual polarity FEC were discussed in [21], [5], [64]. The advantages of FEFSM with single polarity FEC are low copper loss due to less volume of FEC, less leakage flux when compared with dual FEC windings. The field-weakening capability of FEFSM was improved using toroidal DC field winding [22]. The proposed machine had limited torque generation due to the field flux produced by DC field conductors close to the outer surface of the stator, which went through the outside of the stator instead of the rotor as well as high copper losses owing to overlap armature and field windings.

In recent years, research on in-wheel motor for EV drive train system has become more popular due to their several advantages of independent wheel controllability and higher efficiency. In addition, it provides more cabin space caused by the elimination of mechanical transmission gears as conventionally used in most existing EVs with single motor propulsion system configuration. Since the outer-rotor configuration was more suitable for direct drive, the PMFSM with outer-rotor had been proposed only for light EV applications [65]. It provided essentially sinusoidal back-EMF and high torque at low speed. Nonetheless, constant PM flux of
PMFSM made it difficult to control, which required field weakening flux at high speed conditions. 12S-10P outer rotor FEFSM had been proposed and discussed in [66], as illustrated in Figure 2.7(b). Robust rotor structure with high mechanical strength and no PM were clear advantages of this machine while overlap windings will create problem of high copper losses. Three types of low-cost FEFSMs with DC field and AC armature windings with the same coil pitch of one slot pitch (12S-8P), two slot pitches (12S-5P and 12S-7P machines), and different coil pitches of one and three slot pitches (9S-5P), respectively, were analysed and compared in [67]. It was concluded that halving stator slots and rotor poles number can be an effective approach to increase density for FEFSMs.

2.5.2 Design restrictions and specifications for FEFSMs

The design specifications of FEFSMs are illustrated in Table 2.1 in which three major parameters; stator radius, rotor radius and torque density were chosen to differentiate FEFSMs from one another and be further explained in terms of their characteristics. The operating principle of flux switching was obeyed by all these designs. According to the rotor rotation, the flux flows generated by PMs and mmf of FECs were switched and linked with the armature coil alternately while for FEFSM there was no PM, the armature winding and the field excitation coil both were stationary but the magnetic flux linkage in the armature winding could either be

![Figure 2.7: Three-phase FEFSM. (a) Three-phase 24S-10P FEFSM, (b) three-phase outer rotor FEFSM](image-url)
positive or negative depending on the position of the mobile part. The flux generated by field excitation coil flowed from stator to rotor and then from rotor to stator to produce a complete cycle.

### 2.5.3 Flux linkages of various FEFSMs

A key factor for all developed FEFSM models was the phase flux linkage calculation, which created a significant challenge, since the stator had salient poles and the iron core saturation had a significant influence on the motor’s operation. Many research works were published in the past decade in this domain, as [68] that introduced analytical models to calculate the flux linkage, [69] that developed models based on magnetic equivalent circuits, or [70] where the analytical model was created using FEM analysis results. Deterministic optimisation and GA were usually applied for the improvement of flux linkage. Additionally, swarm optimisation [71] could be used to treat several parameters of motor to improve the flux linkage. Although the flux linkage strength of segmental rotor FEFSM was high due to short flux path as compared to salient rotor, the rotor was not robust due to segments, as illustrated in Figure 2.8. All the FEFSMs with salient rotor were the best candidates to be applied for high-speed applications.
Cogging torque of FEFSMs

Cogging torque did not add to electro-magnetic output torque. It only effects in torque pulsations that corresponded to undesirable vibration and acoustic noise. The number of periods, \( N_p \) of the cogging torque waveform over a rotation of one stator tooth pitch was given by [20]:

\[
N_p = \frac{N_{\text{rotor}}}{\text{HCF}(N_{st}, N_{\text{rotor}})}
\]  

(2.1)

where the denominator is defined as the highest common factor (HCF) between stator slots, \( N_{st} \) and number of poles of the rotor, \( N_{\text{rotor}} \). Using the index \( N_p \), the electrical angle of rotation, \( \alpha_{cog} \) for each period of the cogging torque and the number of periods of cogging torque, \( N_{\text{elec}} \) per electrical cycle are therefore,

\[
\alpha_{cog} = \frac{360^0}{N_p N_{st}}
\]  

(2.2)

\[
N_{\text{elec}} = \frac{N_p N_{st}}{N_{\text{rotor}}}
\]  

(2.3)
Various techniques had been published to reduce the cogging torque on both radial type [72-74] and axial type PMFSM [75], left vacant space in the area of FEFSMs, as all the designs discussed above had cogging torque especially various topologies of three-phase FEFSM, which had high cogging torque, as shown in Figure 2.9 [64]. Rotors with stepped skew [76, 77] could be adopted to reduce the cogging torque and torque ripple under various load conditions. Different kinds of notching schemes [78, 79] were also available for cogging torque reduction.

### 2.5.5 Average torque and efficiency

The electromagnetic torque, $T_e$ developed in an electrical machine generally consisted of a reluctance torque component, $T_{rel}$ and an excitation torque component, $T_{exc}$, and might be expressed in a polyphase arrangement as [20],

\[
T_e = \sum_k T_{rel,k} + \sum_k T_{exc,k}
\]  

(2.4)

\[
T_e = \frac{1}{2} \sum_k i_k^2 \frac{dL_k}{d\theta} + \sum_k i_k \frac{d\psi_{exc}}{d\theta}
\]  

(2.5)

![Figure 2.9: Cogging torque of three-phase FEFSM [64]](image-url)
where $L_k$ is the phase winding inductance, $\psi_{exc}$ is the flux linkage due to field excitation, $i_k$ is the phase current, $\theta$ is the electrical angular position of the rotor, and $k= a, b, c$ is the phase designation. As the operation of the FSM with sinusoidal current was with the current placed in phase with the back-EMF, the principal torque was due to $T_{exc}$ and the contribution of $T_{rel}$ was negligible, so that $T_e$ can be expressed as

$$T_e = \frac{P_i(t)}{\omega_r} = \sum_k \frac{e_k(t)i_k(t)}{\omega_r} \approx \sum_k T_{exc,k}$$  \hspace{1cm} (2.6)$$

with $P_i$ being the instantaneous power, $\omega_r$ the rotational speed, and $e_k$ the phase back EMF. The flexible characteristic of the average torque, controllable by both the field and armature current was one of the major advantages of FEFSMs when compared with PMFSM. The first FEFSM developed a torque of just under 1.2 Nm at a speed of 9,500 r/min corresponded to a peak power output of 1170 W, examined in [59]. Peak efficiency of the complete drive was measured at just less than 50%, which was lower than anticipated. The maximum efficiency obtained for 8S-4P FEFSM drive was about 75% at various torque level but the average torque needed improvement at approximately 2 Nm. In [14], the electromagnetic performance of the 12S-10P, 12S-11P, 12S-13P, and 12S-14P FEFSMs were investigated by 2D-FEA analysis and validated experimentally. The average torque-current characteristics of various rotor pole configurations are illustrated in Figure 2.10. The experimental results illustrated that slightly larger torque was produced by 24S-10P FEFSM when compared with 24S-10P PMFSM at lower field current. As the field current increased, at certain levels the stator teeth were saturated and the FEFSM exhibited much lower torque.

A few investigations were undertaken for segmental rotor FEFSM but researchers agreed that this topology was particularly attractive for low-cost operation due to non-overlapping windings and no permanent magnet [20]. The mean torque output increased proportionally with the armature current and field current. At rated field and armature current, the output mechanical torque was
REFERENCES


