DEVELOPMENT OF A NEW SINGLE-PHASE FIELD EXCITATION FLUX SWITCHING MOTOR TOPOLOGY WITH SEGMENTAL ROTOR

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DEVELOPMENT OF A NEW SINGLE-PHASE FIELD EXCITATION FLUX SWITCHING MOTOR TOPOLOGY WITH SEGMENTAL ROTOR

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A thesis submitted in fulfillment of the requirement for the award of the Degree of Master of Electrical Engineering

Faculty of Electrical & Electronic Engineering
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AUGUST, 2016
For my beloved mother and father
Hajah Maznah Ali and Haji Omar Ismail,
My wife and my sons,
Suriani Othman, Muhammad Yusuff and Muhammad Luqman
My siblings and my friends
Thank you for your love, guidance and support
ACKNOWLEDGEMENT

Firstly, in the name of ALLAH, the most gracious and the most merciful. Alhamdulillah, all praises to Allah Almighty for His grace and His blessings given to me for the completion of my master’s studies successfully.

Secondly, I acknowledge, with many thanks, to Ministry of Higher Education (MoHE) and Universiti Tun Hussein Onn Malaysia (UTHM) for awarding me scholarship for my master’s program. I am much honoured to be the recipient for this award. Receiving this scholarship motivates me to maintain a peaceful life and providing me confidence and willingness to achieve my goals.

Thirdly, I wish to express my gratitude to my supervisor, Dr. Erwan Bin Sulaiman for his guidance, invaluable help, advice and patience on my project research. Without his constructive and critical comments, continuous encouragement and good humor while facing difficulties, I could not have completed this research. I am also very grateful to him for guiding me to think critically and independently.

I would also like to thank my lovely wife, Suriani Othman, whose dedication, love and persistent confidence in me, has taken the load off my shoulder. Thank you also to my sons Muhammad Yusuff and Muhammad Luqman who brightened the lives of our family. I would also like to thank my parents and family members for their moral support towards the completion of my study. A sincere thanks to my beloved father Haji Omar Ismail and also to my beloved mother, Hajah Maznah Ali.

Moreover, it has been a very pleasant and enjoyable experience to work in UTHM with a group of highly dedicated people, who have always been willing to provide help, support and encouragement whenever needed. I would like to thank all my fellow friends during my study in UTHM. Life would never have been that existing and joyful without you all. Finally, I would like to thank everybody who was important to the successful realization of this thesis, as well as expressing my apology that I could not mention personally one by one.
ABSTRACT

Diverse topology of three-phase and single-phase Field Excitation Flux Switching Machines (FEFSMs) that have been developed recently have several advantages such as variable flux capability and the single piece structure of rotor suitable for high-speed applications. However, a salient rotor structure has led to a longer flux path resulting in high flux leakage and higher rotor weight. Meanwhile, overlap windings between armature and Field Excitation Coil (FEC) have caused the problems of high end coil increased size of motor and high copper losses. Therefore, a new topology of single-phase non-overlap windings 12S-6P FEFSM segmented rotor with the advantages of less weight and non-overlap between armature coil and FEC windings is presented. The design, flux linkage, back-EMF, cogging torque, average torque, speed, and power of this new topology are investigated by JMAG-Designer via a 2D-FEA. As a results the proposed motor has achieved torque and power of 0.91Nm and 293W, respectively. To prove the simulation result based on 2D-FEA, experimental test is performed and the armature back-EMF was observed with FE current of 4A is supplied. Finally, at the speed of 500 rpm and 3000 rpm, the back-EMF is 2.75 V and 16.13 V, respectively. The simulation results showed reasonable agreement with the experimental results, approximately difference range from 4.9% to 7.4%.
ABSTRAK

Pelbagai topologi motor fasa tunggal dan tiga fasa Motor Penukaran Fluk Penguajaan Medan (FEFSMs) yang telah dibangunkan kebelakangan ini mempunyai beberapa kelebihan seperti keupayaan fluk yang variasi, dan bahagian pemutar tunggal yang kuku sesuai digunakan pada aplikasi yang memerlukan tork, kuasa dan kelajuan tinggi. Walau bagaimanapun, struktur pemutar menonjol telah membawa kepada laluan fluk menjadi panjang telah menyebabkan kadar fluk bocor tinggi dan berat rotor meningkat. Sementara itu, pertindihan antara gegelung angker dan medan penguajian (FE) menyebabkan hujung gegelung dan saiz motor meningkat serta kehilangan tembaga yang tinggi. Oleh itu, satu topologi fasa tunggal 12S-6P FEFSM dengan pemutar bersemen baru dengan pelbagai kelebihan seperti gegelung angker dan FEC tidak bertindih, lebih ringan dan kehilangan tembaga yang rendah telah diperkenalkan. Rekabentuk, hubungan fluk, voltan teraruh (EMF), tork penugalan, tork purata, kelajuan dan kuasa bagi topologi baru ini disiasat dengan menggunakan perisian JMAG-Designer melalui kaedah Analisis Unsur Terhingga dua dimensi (2D-FEA). Hasil analisis ke atas motor yang dicadangkan mendapati tork dan kuasa masing-masing mencapai sebanyak 0.91Nm dan 293W. Keputusan yang diperolehi ke atas motor yang dicadangkan adalamendapati Untuk membuktikan ujian simulasi pada 2D-FEA, ujian secara eksperimen telah dilakukan dan EMF pada gegelung angker telah dicerap dengan arus FE sebanyak 4A telah dibekalkan. Akhir sekali, pada kelajuan 500 rpm dan 3000 rpm, masing-masing voltan teraruh (EMF) adalah 2.75 V dan 16.13 V. Keputusan simulasi menunjukkan perbandingan yang munasabah dengan keputusan eksperimen, dianggarkan julat peratus perbezaan dari 4.9% hingga 7.4%.
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\( N_{cp} \) - Number of periods.
\( \eta \) - Efficiency
\( N_{exc} \) - Electrical angle of rotation for each period of cogging torque
\( \psi_{exc} \) - Flux linkage due to field excitation
\( \theta \) - Electrical angular position of rotor
\( \omega_r \) - Rotational speed
\( \phi \) - Flux
\( F \) - Magnetomotive force
\( \Re \) - Reluctance
\( B \) - Magnetic flux density
\( \ell \) - Stack length
\( P_c \) - Copper loss
\( P_i \) - Iron loss
\( N \) - Number of turns
\( \rho \) - Copper resistivity
\( J_A \) - Armature current density
\( J_F \) - Field current density
\( N_r \) - Number of rotor poles
\( N_s \) - Number of stator slots
\( k \) - Natural number
\( q \) - Number of phases
\( f_e \) - Electrical frequency
\( f_m \) - Mechanical rotation frequency
$\alpha$ - Filling factor
$S$ - Slot area
$I_E$ - Field current
$I_A$ - Armature current
$T$ - Torque
FSM - Flux Switching Motor
PM - Permanent Magnet
FEC - Field Excitation Coil
HE - Hybrid Excitation
FE - Field Excitation
FEA - Finite Element Analysis
CAD - Computer Aided Design
CNC - Computer Numerical Control
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CHAPTER 1

INTRODUCTION

1.1 Research Background

The first concept of flux switching machine (FSM) was founded and published in mid-1950s. FSM consists of all flux sources in the stator. Besides the advantage of brushless machines, FSM has a single piece of iron rotor structure that is robust, and can be used for high-speed applications [1]. 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 [2]. Generally, FSM can be categorised into three groups: permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM have only PM and field excitation coil (FEC), respectively, as their main flux sources, while HEFSM combines both PM and FEC as its main flux source.

Figure 1.1 illustrates the basic operation of FEFSM. Considering Figure 1.1 (a), the excitation of the field and armature windings at positive current creates a flux vector in the north-westerly direction and north-easterly direction, respectively. The combined flux generated by the two coils caused a flux moving vertically upwards and the rotor aligned itself with a pair of vertical stator. Additionally, Figure 1.1 (b) illustrates the current in the armature winding is reversed, while the FEC winding continues being excited in the same direction by the effect of the 180° flux shifting from west-south. The result from the 180° shifting makes the rotor tends to align with the stator poles based on the flux movement in a westerly direction through horizontal stator poles. Therefore, each reversal of current directions in the armature causes the
stator flux vector to switch between horizontal and vertical directions, hence introducing the name FSM [3], [4].

The viability of this design has been demonstrated in applications requiring high power densities and a good level of durability. The single-phase AC motor can be realised with the connection of the FE coil windings to the DC supply and armature windings to the AC supply to achieve the orientation of flux in allowing the rotor rotation [5], [6], [7]. In more recent studies some researchers have developed the use of a segmental rotor construction for switched reluctance motors (SRMs) and two-phase FSMs, which gives significant gains over other topologies.

Whereas segmental rotors are used traditionally to control the saliency ratio in synchronous reluctance machines, the primary function of the segments in this design is to provide a defined magnetic path in conveying the field flux to adjacent stator armature coils as the rotor rotates [8], [9], [10]. As each coil arrangement is around a single tooth, this design gives shorter end-windings than the salient rotor structure, which requires fully-pitched coils. There are significant gains with this arrangement as it uses less conductor materials and may improve the overall motor efficiency.

Hence, this motor has the ability and capability suitable for use in industrial and commercial applications that require low torque and high speed. An example is a conventional fan (table or stand fan), blower, exhaust fan and compressor motors. Currently, most of the commercial applications use induction motors (IMs). Figure 1.2 and Table 1.1 show the example of structure and specifications of single-phase induction motors used in conventional fan, respectively [11]. An induction motor's rotor can be either wound type or squirrel-cage type. For the wound type, the winding
is located on the rotor and stator while for squirrel-cage type the winding is placed only on stator. However, IMs have the disadvantage of having the active part located on the rotor, thus affecting the cooling process and the rotor not being robust [12].

Therefore, the FEFSM with segmental rotor using different windings techniques of induction motor is introduced, where both field excitation coil (FEC) and armature coil windings are placed on the stator. This has led to advantages such as the following; all brushes are eliminated, whilst complete control is maintained over the field excitation flux. The concept of the FEFSM with segmental involves changing the polarity of the flux linking the armature winding by the motion of the rotor [13], [14].

![Figure 1.2: The structure of single-phase induction motor](image)

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<tr>
<td>Items</td>
</tr>
<tr>
<td>Voltage input (Volt)</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>Power (W)</td>
</tr>
<tr>
<td>Torque (Nm)</td>
</tr>
<tr>
<td>Range of speed (rpm)</td>
</tr>
<tr>
<td>Outer diameter of stator (mm)</td>
</tr>
<tr>
<td>Outer diameter of rotor (mm)</td>
</tr>
<tr>
<td>Length of air gap (mm)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
</tbody>
</table>

In this research, a single-phase flux switching motor using a segmental rotor is proposed. This research also describes the principle operation of single-phase non-overlap windings FEFSM 12S-6P with segmental rotor, discusses the prototype fabrication, and compares the back-EMF result of the prototype experimentally.
1.2 Problem Statements

Based on previous literature, single-phase 8S-4P and 12S-6P FEFSMs with salient rotor is suitable for high-speed applications since it has a strong single rotor structure [5], [15], [16], [17]. However, a salient rotor structure has led to a longer flux path resulting in high flux leakage and higher rotor weight. In addition, the overlapped windings between armature and FEC creates the problem of high end coil, which increases the size of the motor.

Therefore, various segmental rotor poles of single-phase non-overlap windings FEFSM with segmental rotor between armature coil and FE coil should be analyzed to create shorter flux path and reduce the coil end problem thus improving their flux linkage, back-EMF, cogging torque, average torque and power versus speed characteristics.

Moreover, the result comparison of back-EMF between simulation and experiment should be carried out to validate the prototype of single-phase non-overlap windings FEFSM with segmental rotor.

1.3 Objectives of the research

The objectives of this research are:

(i) To design various rotor pole of single-phase non-overlap windings FEFSM with segmental rotor.

(ii) To analyse the flux linkage, back-EMF, cogging torque, average torque and power versus speed characteristics of the proposed single-phase non-overlap windings FEFSM with segmental rotor.

(iii) To validate the back-EMF of the prototype of single-phase non-overlap windings 12S-6P FEFSM with segmental rotor.
1.4 Scopes of the Research

Commercial FEA package, JMAG-Designer version 14.1, released by Japan Research Institute (JRI) is used as 2D-FEA solver for this design. The electrical restrictions related with the inverter such as maximum 240V DC inverter current and maximum 11.09A inverter current are set. Assuming the air coolant system is employed as the cooling system for the machine, the limit of the current density is set to a maximum of 30A\(_{rms}\)/mm\(^2\) for armature windings and 30A/mm\(^2\) for FE windings, respectively. In various rotor poles studies, the design of the machine is focused only on 4 designs, 12S-3P, 12S-6P, 12S-9P, and 12S-15P. The stator outer diameter, the stator inner diameter, the back inner width of stator, tooth width of stator, the motor stack length, the rotor outer diameter, the shaft of rotor and the air gap having dimensions 75 mm, 45 mm, 5 mm, 20.3 mm, 44.5mm, 15 mm and 0.25 mm, respectively will be kept constant for all designs. The materials used for stator and rotor are silicon electric steel 35A250, while armature and FEC winding are copper.

Therefore, design 2D and 3D part sketches during the prototype process of the proposed single-phase 12S-6P FEFSM with segmental rotor should be done with Solidworks 2014 software. In addition, coil winding is set to 88 turns for both FEC and armature coil windings. While, the silicon electric steel 35A250 is cut into 58 pieces. To perform the back-EMF test by experimental, motor measuring system that has been calibrated must be provided and connected to the motor test. The limit of DC power supply and speed of DC motor (prime mover) are set to 4A and 3,000rpm, respectively.
1.5 Thesis Outlines

This thesis deals with the development of FEFSM with segmental rotor. Basically, 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 toothed and segmental rotor. Problems of existing motors employing segmental rotor, research objectives and research scope are discussed in this chapter.

(b) Literature review
This chapter defines the overview and classifications of various FSMs. Among the three types of FSM - Permanent Magnet Flux Switching Machine (PMFSM), Field Excitation Flux Switching Machine (FEFSM) and Hybrid Excitation Flux Switching Machine (HEFSM), FEFSM is the best type to be considered as it does not use PM. In addition, a variety of designs of FEFSM with performance have been clearly explained. Besides, the analysis and all the formulas used to design FSM have been described. The final section describes the overviews of development, testing, and validation of the performance of prototype that has been done by previous researchers.

(c) Research Methodology
The project implementation has been divided into three stages including the designs of various rotor poles study of single-phase FEFSM with segmental rotor, analysis of performance for single-phase FEFSM with segmental rotor using 2D-FEA with JMAG Designer and prototype fabrication and results comparison. Stage 1 is divided into two parts that are geometry editor and JMAG Designer, while stage 2 is divided into two parts that are no-load and load analysis by 2D FEA. Finally, stage 3 has three phases, which are designing a FEFSM in 3D, fabrication of single-phase 12S-6P FEFSM with segmental rotor, and experimentation and validation of prototype back-EMF.

(d) Results and Discussions
This chapter defines the design, performance analyses, and development, testing, and validation of the performance of the FEFSM prototype. The 12S-6P is the best design and is selected for future 2D-FEA load-analysis and
development of the prototype. Based on 2D-FEA by JMAG, the flux linkage, maximum torque, and power is 0.041Wb, 0.9Nm, and 293W, respectively. In the fabrication, there are four types of methods that have been used for the fabrication of prototype single-phase 12S-6P using CNC machines, 3D printer, and coil windings manually. Materials used in the prototype are silicon electric steel 35A250, aluminum, stainless steel, ABS plastic, and copper wire. The experimental test shows the speed of 500rpm and 3,000rpm for the back-EMF are 2.75V and 16.13V, respectively. The average percentage difference between the experimental and JMAG simulation is 6.2%.

(e) Conclusions and Future works
The final chapter describes and concludes the research and suggestions for future works are described in this chapter.

1.6 Chapter Summary

This chapter briefly describes the type of motors used on the existing system fan and identifying motor weaknesses. The single-phase non-overlap windings FEFSM with segmental rotor is introduced to overcome the drawbacks of single-phase overlap windings FEFSM with salient rotor. In addition, the objectives and scope of the research are also briefly described in this chapter to explain the implementation of this research.
CHAPTER 2

LITERATURE REVIEW ON FEFSM

2.1 Introduction

This chapter defines the overview and classifications of various FSMs. Among the three types of FSM are PMFSM, FEFSM and HEFSM. FEFSM is the best type to be considered and will be emphasised more due to its does not use PM. Besides, the analysis and all the formulas used to design FSM have been described. The final section describes the overviews of development, testing, and validation of the performance of prototype that has been done by previous researchers.

2.2 Introduction to Electric Motor

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. The reverse the process, which is producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo. Some electric motors can also be used as generators, for example, a traction motor on a vehicle may perform both tasks. Electric motors and generators are commonly referred to as electric machines.

Electric motors can be divided into two types; alternating current (AC) electric motors and direct current (DC) electric motors. The DC electric motors will not work if supplied with AC supply, and vice versa. DC motors use batteries with DC supply as it has an advantage of simple control principle. However, usage of the commutator and brush, makes them less reliable and unsuitable for maintenance-free drives. The speed control of DC and AC motors are also different. For DC motors, the speed is
controlled by varying the current in the DC windings, while the speed of AC motors is influenced by the frequency.

There are three types of AC motors, which are asynchronous motor or Induction Motor (IM), synchronous motor (SM), and switched reluctance motor (SRM). IM is divided into two, squirrel cage and wound cage. Most industrial uses IM since the motor is durable and inexpensive. SM can be classified as permanent magnet SM (PMSM), field excitation SM (FESM), hybrid excitation SM (HESM) and flux switching motor (FSM). FSM can be further classified as permanent magnet FSM (PMFSM), field excitation FSM (FEFSM), and hybrid excitation FSM (HEFSM). Figure 2.1 illustrates the classification of the main types of electric motors [18].

Induction motor (IM) action involves induced currents in coils on the rotating armature. IMs use shortened wire loops on a rotating armature and obtain their torque from currents induced in these loops by the changing magnetic field produced in the stator (stationary) coils. The induced voltage in the coil shown drives current and results in a clockwise torque. Note that this simplified motor will turn once it is started in motion, but has no starting torque. Various techniques were used to produce some asymmetry in the fields to give the motor a starting torque [19], [20].

![Figure 2.1: The Classification of the main types of Electric Motors](image)

The switched reluctance motor (SRM) is an electric motor that runs by reluctance torque. SRM is a kind of motor relying on the working principle of magneto
resistive effect, and initial motor performance is imperfect [21]. With the growth of high-functioning and high power electronic devices as well as the diverse implementations of intelligent control, SRM has been actively developed [22]. Unlike common DC motor types, power is delivered to windings in the stator (case) rather than the rotor [23]. This greatly simplifies mechanical design as power does not have to be delivered to a moving part, but it complicates the electrical design as some sort of switching system that needs to be used to deliver power to the different windings. With modern electronic devices this is not a problem, and the SRM is a popular design for modern motors. Its main drawback is torque ripple.

Synchronous motors (SMs) are naturally constant-speed motors. They operate in synchronism with line frequency and are commonly used where precise constant speed is required. The SM is an electric motor that is driven by AC power consisting of two basic components: a stator and rotor. Typically, a capacitor connected to one of the motor's coil is necessary for rotation in the appropriate direction. The outside stationary stator contains copper wound coils that are supplied with an AC current to produce a rotating magnetic field. The magnetised rotor is attached to the output shaft and creates torque due to the stator rotating field. The motor's synchronous speed is determined by the number of pair poles and is a ratio of the input (line) frequency. In the mid-1950s, the concept of FSM was founded and first published [24]. FSM is a new category of SMs.

2.3 Flux Switching Motor (FSM)

Generally, FSM can be categorised into three groups: permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM). Both PMFSM and FEFSM have only PM and field excitation coil (FEC), respectively, as their main flux sources, while HEFSM combines both PM and FEC as its main flux source. Figure 2.2 illustrates the general classification of FSMs.
FSM consists of the rotor and stator. The rotor consists of a single structure, which is an iron core, thus allowing its simple construction and inherent robustness to be retained while both field and armature windings are on the stator. These contribute to major advantages where all brushes are eliminated, whilst complete control is maintained over the field flux. The operation of the motor is based on the principle of switching flux. The term “flux switching” is coined to describe motors in which the stator tooth flux switches polarity following the motion of a salient pole rotor [25]. All excitation sources are on the stator with the armature and field allocated to alternate stator teeth. Figure 2.3 illustrates the various types of FSMs [26], [27].

Flux is produced in the stator of the motor by a permanent magnet or by DC current flowing in the field winding. The orientation of the field flux is then simply switched from one set of stator poles to another by reversing the polarity of the current in the armature winding. As a result of preliminary studies, the FEFSM were selected and used for detailed analysis. This is because FEFSM does not use PM as a source to produce flux and indirectly contributes to a reduction in the cost of construction of a motor without reducing any ability of the motor [28], [29], [30].
Figure 2.3: Various types of FSMs [26], [27]

(a) C-core PMFSM
(b) E-core PMFSM
(c) FEFSM with segmental rotor
(d) FEFSM with salient rotor
(e) Outer rotor HEFSM
(f) HEFSM with non-overlap windings
2.3.1 Field Excitation Flux Switching Machines

Among several classes of FSMs, the FEFSMs offer numerous advantages such as magnet-less machine, low cost, simple construction, and variable flux control capabilities that are suitable for various performances. The concept of the FEFSMs involves changing the polarity of the DC Field Excitation Coil (FEC) flux linking with the armature coil flux, with respect to the rotor position. To form the FEFSMs, the PM excitation on the stator of conventional PMFSMs is replaced by DC FEC windings for their main flux sources [13]. Figure 2.4 shows the operating principle of the FEFSM in which a field flux path is generated by MMF of FEC at two different rotor positions when the FECs are energised with DC current. The line with arrows depicts the field flux path.

The direction of the FEC fluxes into the rotor is demonstrated in Figure 2.4 (a) and Figure 2.4 (b) while the direction of FEC fluxes into the stator is represented in Figure 2.4 (c) and Figure 2.4 (d), correspondingly to produce a complete one cycle flux. The flux linkage of FEC switches its polarity by following the movement of the salient pole rotor, which creates the word “flux switching”. Each reversal of armature current shown by the transition between Figure 2.4 (a) and Figure 2.4 (b), causes the stator flux to switch between the alternate stator teeth. The flux does not rotate but shifts clockwise and counterclockwise with each armature-current reversal. With the rotor inertia and appropriate timing of the armature current reversal, the reluctance rotor can rotate continuously at a speed controlled by the armature current frequency. The armature winding requires an alternating current reversing in polarity in synchronism with the rotor position.

This FEFSM can be divided into two types, namely Field Excitation Flux Switching Machine with Salient Rotor and Filed Excitation Flux Switching Machine with Segmental Rotor. Both rotors have same characteristics but different designs.
The previous FEFSM with salient rotor configurations and dimensions are illustrated in Figure 2.5 and Table 2.1, respectively. Figure 2.5(a) shows the single-phase 12S-6P FEFSM [16]. The single-phase FEFSM can be considered a very simple machine to manufacture; it requires two power electronic controllers for armature coil and DC FEC. Thus, it has the potential to be extremely low cost, although only in high-volume applications. Furthermore, being an electronically commutated brushless machine, FEFSM inherently offers longer life, and very flexible and precise control of torque, speed, and position at no additional cost. However, the single-phase FEFSMs suffer with problems of low starting torque, large torque ripple, fixed rotating direction, and overlapped windings between armature coil and DC FEC [27].
In addition, three-phase FEFSM with salient rotor has also been introduced to be used in HEV applications as shown in Figure 2.5(b) and Figure 2.5(c) [13], [28], [31]. Table 2.2 shows a summary of performance for each type of FEFSM with salient rotor. The table clearly shows that the combination of 12S-10P FEFSM salient rotor is ranked highest, followed by a three-phase 12S-14P FEFSM salient rotor, and the lowest is a single-phase 12S-6P FEFSM with salient rotor. This evaluation is based from these three parameters: back-EMF, torque, and power. Although the three-phase 12S-10P FEFSM produced the back-EMF 290V, the torque and power of this machine is the highest, with 212.9Nm and 127.3kW, respectively. Compared with the three-phase 12S-14P and single-phase 12S-6P FEFSM with salient rotor, their torque and power is less than the three-phase 12S-10P with salient rotor. For the three-phase 12S-14P, the torque is 164.1Nm and power is 61.5kW. While for single-phase 12S-6P, the torque and power is 38.2Nm and 31.6kW, respectively.

Figure 2.5: Examples of FEFSM with salient rotor [13], [16], [28], [31]
2.3.3 Field Excitation Flux Switching Machine with Segmental Rotor

The discussion of flux switching machine in the previous sections was with rotors with toothed or slotted structure. With a complete loop coil-turn arrangement, a standard configuration in electrical machines with multi-turn windings, the windings are longpitched, if not fully-pitched, and invariably overlap. In [32], Mecrow et al suggested a structure of producing mutual coupling of single-tooth coils using a segmental rotor for switched reluctance motor configurations.

This configuration maintains the production of higher torque densities by the principle of the changing mutual inductance [33], [34], but has a further advantage of reduced copper usage and power loss due to resulting shorter end-windings. Use of a segmental rotor as applied to flux switching machines, turns the structure for field-winding excitation proposed by Pollock et al [3] and presented in the previous section, into one with single-tooth windings. Thus, for flux switching machines employing a segmental rotor, there is, firstly, the attraction of achieving higher torque densities due

Table 2.1: The main parameters of FEFSM with salient rotor [13], [16], [28], [31]

<table>
<thead>
<tr>
<th>Items</th>
<th>12S-6P</th>
<th>12S-10P</th>
<th>12S-14P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phase</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rated speed (r/min)</td>
<td>1,000</td>
<td>3,000</td>
<td>1,200</td>
</tr>
<tr>
<td>Max. DC-bus voltage inverter (V)</td>
<td>360</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Max. current density in armature winding, $J_A$</td>
<td>10</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>Max. current density in excitation winding, $J_E$</td>
<td>10</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>90</td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td>Motor stack length (mm)</td>
<td>25</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Air gap length</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2.2: Performances of FEFSM with salient rotor [13], [16], [28], [31]

<table>
<thead>
<tr>
<th>Items</th>
<th>12S-6P</th>
<th>12S-10P</th>
<th>12S-14P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-EMF(V)</td>
<td>50.4</td>
<td>290</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
<td>38.2</td>
<td>212.9</td>
<td>164.1</td>
</tr>
<tr>
<td>Maximum Power (kW)</td>
<td>31.6</td>
<td>127.3</td>
<td>61.5</td>
</tr>
</tbody>
</table>
to operating with bipolar flux and secondly, a reduction of copper losses and material due to shorter end-windings.

The basic structure employing a segmented rotor is shown in Figure 2.6 and is modelled from the basic principle reported in [3]. For the two rotor positions shown in the figure, while the field flux F1 and F2 are unchanged, there is a change of polarity of the armature flux linkages on A1 and A2 as the rotor segments S1 as S2 rotate.

![Figure 2.6: Basic segmental rotor structure with FE only [35](a) Armature at positive (b) Armature at negative](image)

Figure 2.6 illustrates in a simplified rectilinear arrangement how a segmental rotor can achieve flux switching for a concept of four stator teeth and two rotor segments, with field excitation only applied to coils winding round teeth F1 and F2. For the different rotor positions shown, coupling between adjacent coils on the teeth is through segments. The motion of the rotor not only varies flux in the armature teeth A1 and A2, but also changes its polarity. This results in coils winding round teeth A1 and A2 experiencing a bipolar AC magnetic field, with EMF being induced. Armature tooth flux switches polarity at two points in a cycle by two distinct presentations of the rotor segment.

The first presentation for flux to switch polarity is when the trailing edge of one segment and the leading edge of the next segment have equal overlap over the armature tooth, while the second presentation is when a segment is centered with the armature tooth, as illustrated in Figure 2.7 (b) and Figure 2.7 (d). Even though the flux linkage of the armature winding is zero at these positions, there is considerably higher flux density at the tip and the root of the armature tooth for position (b) than for position (d).
Figure 2.7: FEFSM with segmental rotor operating principles under FE excitation
Figure 2.8 shows the cross sectional views of two topologies of three phase FEFSM with segmental rotor reported in [35], [36], [37]. From figure, clearly shows both the FEC and the armature coils are non-overlapped, and it can reduce the usage of copper and rate of copper loss [38]. From Figure 2.8 (a), the machine have 12 slot of armature, 12 slot of FECs, and six poles of rotor and the FECs are allocated uniformly in the middle of each armature coil slot. Eight stator slots and four rotor poles of FEFSM with segmental rotor is shown in Figure 2.8 (b).

It is clear from the figure that four pole magnetic field is established when direct current is applied to the FEC winding in four of the slots. The other four slots hold an armature winding that is also pitched over two stator teeth. A set of four stator poles carrying flux and the position of the rotor is decided by direction of the current in the armature winding.

(a) Three-phase 24S-10P  (b) Three-phase 12S-8P

Figure 2.8: Examples of FEFSM with segmental rotor [35], [36], [37]

The limits on the segment span are set by the minimum separation required to prevent any appreciable flux crossing to adjacent segments and the segment pitch, which is controlled by the number of segments employed. Table 2.3 shows the main parameters of FEFSM with segmental rotor. Normally, for three-phase, the DC-bus maximum voltage inverter is set to 650V. The estimated speed rate most commonly used is from 500r/min to 1,200r/min. The maximum FEC current desity, $J_E$ and armature current density, $J_A$ is 30A/mm$^2$ and 30A$\text{rms}$/mm$^2$, respectively. In addition, from the proposed earlier design [36], [37], the highest parameter for outer stator diameter, motor stack length, and air gap length is 150mm, 150mm, and 0.5mm, respectively.
Table 2.4 shows the summary performance of previous analysis of FEFSM with segmental rotor. The table shows that the three-phase 12S-8P FEFSM with segmental rotor has advantages of high torque 25Nm, followed by three-phase 12S-10P FEFSM with segmental rotor. In terms of the back-EMF voltage, only 12S-8P FEFSMs with segmental rotor design is found, which is it achieved 38V. If viewed in terms of power, the 12S-8P FEFSM segmental rotor design is better because based on the theory, the power is proportional to the torque and speed.

Although the design of the three-phase 12S-8P is said to have better performance, but the combination between rotor teeth and stator teeth that are not balanced can interfere flux path. Which is a combination of less segmented rotor will increase the width of the rotor teeth. This causes a flow of flux from the stator to the segmented rotor becomes larger and easier. In addition, the use of a 8 segmented rotor teeth is found to have led to the design of complex design and increase the weight of the rotor as well as the fabrication process will becomes more complicated compared with the use of a less segmented rotor teeth. From the aspect of application, previous FEFSM segmented rotor developed only focused on applications requiring torque, power and high speed such as HEV applications and this prompted the researchers to conduct studies related to FEFSM three-phase only.

Table 2.3: The main parameters of FEFSM with segmental rotor [35], [36], [37]

<table>
<thead>
<tr>
<th>Items</th>
<th>24S-10P</th>
<th>12S-8P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phase</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rated speed (r/min)</td>
<td>1,200</td>
<td>500</td>
</tr>
<tr>
<td>Max. DC-bus voltage inverter (V)</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Max. current density in armature winding, $J_A$</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>Max. current density in excitation winding, $J_E$</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Motor stack length (mm)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Air gap length</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2.4: Performances of FEFSM with segmental rotor [35], [36], [37]

<table>
<thead>
<tr>
<th>Items</th>
<th>24S-10P</th>
<th>12S-8P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-EMF (V)</td>
<td>NA</td>
<td>38</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
<td>21.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Maximum Power (kW)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Therefore, the design FEFSM segmented rotor should be diversified to a single-phase motor and a combination stator and rotor is calculated by using the Formula (2.1). This indirectly enables it to be used in applications characterized by torque, low-speed power and as a fan, blower, compressor air conditioner, washing machine, blender, vacuum cleaner and other home appliances. In practice, significant benefits of short end-windings appear with the 12S-6P configurations if a single-phase topology is pursued.

2.4 Overview of Design and Analysis of FEFSMs

For design and performance analysis (2D-FEA), a commercial FEA package, JMAG-Designer ver.12.0, released by Japan Research Institute (JRI) is used. Initially, the rotor, stator, armature coil, and FEC of the proposed FEFSM is drawn by using Geometry Editor followed by the setup of materials, conditions, circuits, and properties of the machine, which are set in JMAG Designer. The electrical steel 35H210 is used for rotor and stator body. The design developments of both parts are established in Figure 2.9 [31].

![Flowchart](attachment:flowchart.png)

(a) Geometry Editor  
(b) JMAG-Designer

Figure 2.9: Design implementation of the proposed FEFSM [31]
For the calculation of the combination of slot and pole motor of FEFSM, Equation (2.1) is used. Where \( N_r \) is represented as the number of rotors, \( N_s \) is the number of stator slot, \( k \) is the integer from 1 to 5, and \( q \) is the number of phases. Meanwhile, Equations (2.2) and (2.3) are used to estimate the number of windings on the armature coils and the FECs, respectively. From the equation, \( N \) refers to the total winding, \( J \) is the current density, \( \alpha \) is filling factor, \( S \) is the total area of the slot, and \( I \) is current. The symbols \( A \) and \( E \) in each equation indicate the use of armature and FE, respectively.

\[
N_r = N_s \left[ 1 \pm \frac{k}{2q} \right] \quad (2.1)
\]

\[
N_A = \frac{J_A \alpha S_A}{I_A} \quad (2.2)
\]

\[
N_E = \frac{J_E \alpha S_E}{I_E} \quad (2.3)
\]

The value of input current of armature coils, \( I_A \) is calculated by using Equation (2.4). Then, Equation (2.5) is used to calculate the input current of FE coils, \( I_E \) [31], [39].

\[
I_A = \frac{J_A \alpha S_A \sqrt{2}}{N_A} \quad (2.4)
\]

Where,
\( I_A \) = Input current of armature coil  
\( J_A \) = Armature coil current density (set to maximum of 30 A/mm\(^2\))  
\( \alpha \) = Armature coil filling factor (set to 0.5)  
\( S_A \) = Armature coil slot area  
\( N_A \) = Number of turns of armature coil

\[
I_E = \frac{J_E \alpha S_E}{N_E} \quad (2.5)
\]

Where,
\( I_E \) = Input current of FE coil  
\( J_E \) = FEC current density (set to maximum of 30 A/mm\(^2\))  
\( \alpha \) = FEC filling factor (set to 0.5)  
\( S_E \) = FEC slot area  
\( N_E \) = Number of turns of FEC
According to the principle of FSM, the general relationship between the electrical frequency and the mechanical rotation frequency can be expressed as,

\[ f_e = N_r f_m \]  \hspace{1cm} (2.6)

From Equation (2.6), it is clear that the electrical frequency, \( f_e \) is directly proportional to the number of rotor poles, \( N_r \) and the mechanical rotation frequency, \( f_m \) is double that of the electrical frequency of conventional interior permanent magnet synchronous motor (IPMSM), when the FSMs use the same number of poles [40]. After calculating all parameters, process simulation is run to perform further analysis. Information such as the back-EMF, flux characteristics, and torque are obtained directly from the simulation process.

Any changes in the magnetic environment of a coil of wire causes a voltage (EMF) to be induced in the coil. The voltage will be generated when any change is produced. The change could be produced by changing the magnetic field strength, moving a magnet towards or away from the coil, moving the coil into or out of the magnetic field, and rotating the coil relative to the magnet.

Faraday's Law summarises the ways voltage can be generated. This law states that if flux passes through a turn of a coil of wire, a voltage will be induced in the turn directly proportional to the negative of the rate of change in the flux with respect to time, as in Equation (2.7).

\[ E_{ind} = -\frac{d\phi}{dt} \]  \hspace{1cm} (2.7)

Where \( E_{ind} \) is the voltage induced in the turn of the coil and \( \phi \) is the flux passing through the turn. If a coil has \( N \) turns and if the same flux passes through all of them, then the voltage induced across coil the whole coil is given by Equation (2.8)

\[ E_{ind} = -N \frac{d\phi}{dt} \]  \hspace{1cm} (2.8)

Where \( E_{ind} \) is the voltage induced in the turn of the coil, \( \phi \) is the flux passing through the turn, and \( N \) is the number of turns of wire in coil [41].

When back-EMF is generated by a change in magnetic flux according to Faraday's Law, the polarity of the back-EMF is such that it produces a current whose
magnetic field opposes the change, which produces it. The induced magnetic field inside any loop of wire always acts to keep the magnetic flux, $B$, in the loop constantly. If the $B$ field is increasing, the induced field acts in opposition to it. If it is decreasing, the induced field acts in the direction of the applied field to try to keep it constant [42].

Cogging torque does not add to electro-magnetic output torque, it only affects in torque pulsations, which correspond to undesirable vibration and acoustic noise. The number of periods, $N_{cp}$, of the cogging torque waveform over a rotation of one stator tooth pitch is given by

$$N_{cp} = \frac{N_r}{HCF\{N_s, N_r\}}$$  \hspace{1cm} (2.9)

Where the denominator is defined as the highest common factor (HCF) between $N_s$ and $N_r$, while $N_r$ being the number of poles of the rotor. Using the index $N_p$, the electrical angle of rotation, $\theta_{cog}$, for each period of the cogging torque and the number of periods of cogging torque, $N_{cte}$ per electrical cycle are therefore

$$\theta_{cog} = \frac{360^\circ}{N_{cp}N_s}$$  \hspace{1cm} (2.10)

and

$$N_{cte} = \frac{N_{cp}N_s}{N_r}$$  \hspace{1cm} (2.11)

respectively.

Therefore, all of the above equations can be simplified as,

$$N_{cte} = \left\lceil \frac{360^\circ}{N_r} \right\rceil$$

$$N_{cte} = \frac{360^\circ}{N_s} - \frac{360^\circ}{N_r}$$

Hence,

$$N_{cte} = \frac{N_s}{N_r - N_s}$$  \hspace{1cm} (2.12)

The electromagnetic torque, $T_e$ developed in an electrical machine generally consists of a reluctance torque component, $T_{rel}$ and an excitation torque component, $T_{exc}$, and maybe expressed in a polyphase arrangement as [35]
REFERENCES


