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

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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

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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 Pengujaan Medan (FEFSMs) yang telah dibangunkan kebelakangan ini mempunyai beberapa kelebihan seperti keupayaan fluk yang variasi, dan bahagian pemutar tunggal yang kukuh 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 pengujaan (FE) menyebabkan hujung gegelung dan saiz motor meningkat serta kehilangan tembaga yang tinggi. Oleh itu, satu topologi fasa tunggal 12S-6P FEFSM dengan pemutar bersegmen 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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LIST OF SYMBOLS AND ABBREVATIONS

N_{ctp}	-	Number of periods.
η	-	Efficiency
N_{cte}	-	Electrical angle of rotation for each period of cogging torque
Ψ_{exc}	-	Flux linkage due to field excitation
θ	-	Electrical angular position of rotor
ω_r	-	Rotational speed
ϕ	-	Flux
F	-	Magnetomotive force
$\Re$	-	Reluctance
B	-	Magnetic flux density
ℓ	-	Stack length
P_c	-	Copper loss
P_i	-	Iron loss
N	-	Number of turns
ρ	-	Copper resistivity
J_A	-	Armature current density
J_E	-	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

α	-	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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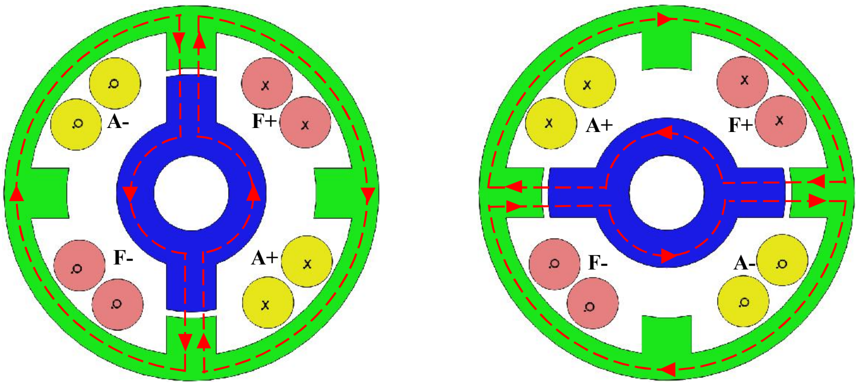
CHAPTER 1

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



(a) (b)

Figure 1.1: Basic principle of FSM

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].

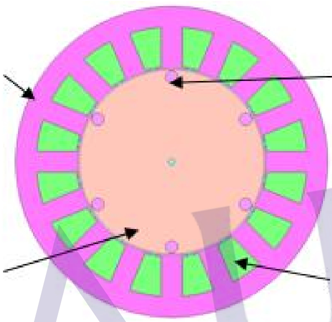


Figure 1.2: The structure of single-phase induction motor

Table 1.1: 1-Ø Induction motor specifications

Items	Parameters
Voltage input (Volt)	240
Frequency (Hz)	50
Power (W)	60
Torque (Nm)	0.4
Range of speed (rpm)	1455-1465
Outer diameter of stator (mm)	75
Outer diameter of rotor (mm)	44.5
Length of air gap (mm)	0.25
Weight (kg)	0.91

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].

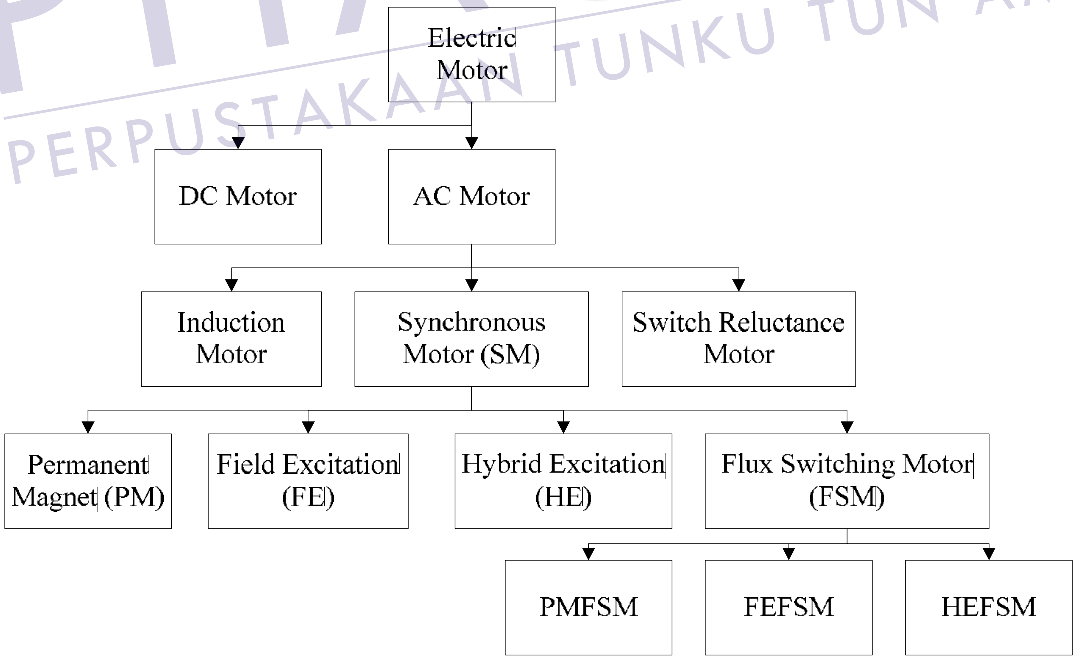


Figure 2.1: The Classification of the main types of Electric Motors

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

REFERENCES

[1] M. M. a Mazlan, E. Sulaiman, and T. Kosaka. Design study of single phase outer-rotor hybrid excitation flux switching motor for hybrid electric vehicles. *2014 IEEE 8th International, Power Engineering and Optimization Conference (PEOCO)*. March 24-25. Langkawi. 2014. pp. 138–143.

[2] E. Sulaiman. Design studies on less rare-earth and high power density flux switching motors with hybrid excitation/wound field excitation for hev drives, Nagoya Institute of Technology Nagoya, Japan, 2012.

[3] C. Pollock and M. Wallace, The flux switching motor, a DC motor without magnets or brushes. *Thirty-Fourth IAS Annual Meeting on Industry Applications Conference*. Phoenix, AZ. 1999. Vol. 3. pp. 1980-1987.

[4] M. Jenal, S. A. Hamzah, F. Khan, H. A. Soomro and E. Sulaiman. Performance investigations of flux switching machines for light weight electric vehicles. *2015 IEEE Conference on Energy Conversion (CENCON)*. October 19-20. Johor Bahru. 2015. pp. 78-83.

[5] C. Pollock, H. Pollock, R. Barron, J. R. Coles, D. Moule, A. Court, and R. Sutton. Flux-switching motors for automotive applications. *IEEE Transactions on Industry Applications*. 2006. 42(5): 1177 - 1184.

[6] C. Pollock. Electronically controlled flux switching motors : a comparison with an induction motor driving an axial fan. *The 29th Annual Conference of the IEEE on Industrial Electronics Society, 2003. IECON '03*. 2003. vol 3. pp. 2465-2470.

[7] H. Pollock, C. Pollock, R. T. T. Walter, B. V. V Gorti, L. Uk, R. T. T. Walter, and B. V. V Gorti. Low cost, high power density, flux switching machines and drives for power tools. *38th IAS Annual Meeting, Industry Applications Conference*. 2003. vol. 3. pp. 1451–1457.

[8] B. C. Mecrow, J. W. Finch, E. a. El-Kharashi, and a. G. Jack. Switched reluctance motors with segmental rotors. *IEE Proceedings - Electric Power Applications*. 2004. 149(4): 245.

[9] B. C. Mecrow, E. a. El-Kharashi, J. W. Finch, and A. G. Jack. Preliminary performance evaluation of switched reluctance motors with segmental rotors. *IEEE Transactions on Energy Conversion*. 2004. 19(4): 679-686.

[10] W. H. R. Cao, Y. Jin, Y. Zhang. A new general design method of segmented-rotor wound field flux-switching motors with complementary magnet circuit. *2015 IEEE Magnetics Conference (INTERMAG)*. May 11-15. Beijing. 2015. pp. 4731.

[11] Stand fan sf1802 instruction manual. Retrieved on Jun 30, 2015, from http://www.khind.com.my/i_prod/Stand Fan SF 1802 Instruction Manual.pdf.

[12] C. S. Liu, J. C. Hwang, and P. C. Chen. Improvement of driver efficiency for the single-phase motor. *2012 IEEE International Symposium on Industrial Electronics (ISIE)*. May 28-31. Hangzhou. 2012. pp. 664 - 667.

[13] E. Sulaiman, T. Kosaka, and N. Matsui. A new structure of 12Slot-10Pole field-excitation flux switching synchronous machine for hybrid electric vehicles. *Proceedings of the 2011-14th European Conference on Power Electronics and Applications (EPE 2011)*. August 30 - September 1. Birmingham. 2011. pp. 1 - 10.

[14] Y. Tang, J. J. H. Paulides, T. E. Motoasca, and E. a. Lomonova. Flux-switching machine with DC excitation. *IEEE Transactions on Magnetics*. 2012. 48(11): 3583-3586.

[15] C. Pollock, H. Pollock, R. Barron, R. Sutton, J. Coles, D. Moule, a. Court, L. E. Uk, R. Barron, R. Sutton, J. Coles, D. Moule, a. Court, and T. R. W. Conekt. Flux switching motors for automotive applications. *IEEE Transactions on Industry Applications*. 2006. 42(5): 1177-1184.

[16] Y. J. Zhou and Z. Q. Zhu. Comparison of Low-Cost Single-Phase Wound-Field Switched-Flux Machines. *IEEE Transactions on Industry Applications*. 2014 50(5): 3335-3345.

[17] Y. J. Zhou, Z. Q. Zhu, and S. Sheffield. Comparison of Low-Cost Wound-Field Switched-Flux Machines. *2013 IEEE Energy Conversion Congress and Exposition*. September 15 - 19. Denver, CO. 2013. pp. 904-911.

[18] Electrical Motor | Types Classification and History of Motor | Electrical4u. Retrieved on Jun 09, 2015, from http://www.electrical4u.com/electrical-motor-types-classification-and-history-of-motor/.

[19] A. J. Pansini. *Basics of Electric Motors: Including Polyphase Induction and Synchronous Motors.* Pennwell Publishing Company. 1996.

[20] A. Hughes and B. Drury. *Electric Motors and Drives: Fundamentals, Types and Applications*. Newnes. 2013.

[21] S. Yaning and W. Weiping. Study on switch reluctance motor drive system using variable structure control with sliding. *2010 IEEE International Conference on Information and Automation (ICIA)*. June 20 - 23. Harbin. 2010. pp. 2154-2157.

[22] M. B. Belhadi, A. Kolli, G. Krebs, and C. Marchand. Evaluation of torque-speed curve of switched reluctance motor with segmental rotor. *2012 XXth International Conference on Electrical Machines (ICEM).* September 2-5. Marseille. 2012. pp. 250-255.

[23] Michael T. DiRenzo (2000). Switched Reluctance Motor Control - Basic Operation and Example. Retrieved on June 08, 2015, from http://www.ti.com/lit/an/spra420a/spra420a.pdf.

[24] S. E. Rauch and L. J. Johnson. Design Principles of Flux-Switch Alternators. *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*. 1955. 74(3): 1261-1268.

[25] J. H. Walker. The theory of the inductor alternator. *Journal of the Institution of Electrical Engineers - Part II: Power Engineering.* 1942. 89(9): 227-241.

[26] M. Z. Ahmad, E. Sulaiman, M. Jenal, W. M. Utomo, S. A. Zulkifli, and A. A. Bakar. Design investigation of three phase HEFSM with outer-rotor configuration. *2013 IEEE Conference on Clean Energy and Technology (CEAT)*. November 18-20. Lankgkawi. 2013. pp. 220-225.

[27] E. Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad, and T. Kosaka. Performance comparison of 24s-10p and 24s-14p field excitation flux switching machine with single dc-coil polarity. *2013 IEEE 7th International on Power Engineering and Optimization Conference (PEOCO)*, June 3-4. Langkawi. 2013. pp. 46-51.

[28] E. Bin Sulaiman, T. Kosaka, and N. Matsui. Design study and experimental analysis of wound field flux switching motor for HEV applications. *2012 XXth International Conference on Electrical Machines (ICEM)*. September 2-5. Marseille. 2012. pp. 1269-1275.

[29] S. N. U. Zakaria and E. Sulaiman. Magnetic flux analysis of E-core hybrid excitation flux switching motor with various topologies. *2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE),* October 8-10. Johor Bahru. 2014. pp. 95-98.

[30] Y. Li, W. Xu, and S. Member. Optimization and performance analysis of E-core and C-core flux-switching permanent-magnet machines for electric vehicle applications. *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*. October 22-25. Hangzhou. 2014. pp. 53-59.

[31] Z. A. Husin, E. Sulaiman, M. Mubin, and A. Mazlan. Performances comparison of 12s-10p and 12s-14p of field excitation flux switching motor for hybrid electric vehicle. *The 2nd Power and Energy Conversion Symposium (PECS 2014)*. May 12. Melaka. 2014. pp. 195–201.

[32] B. C. Mecrow, E. a. El-Kharashi, J. W. Finch, and a. G. Jack. Segmental rotor switched reluctance motors with single-tooth windings. *IEE Proceedings - Electric Power Applications.* 2003. 150(5): 591-599.

[33] B. C. Mecrow. New winding configurations for doubly salient reluctance machines. *IEEE Transactions on Industry Applications*. 1996. 32(6): 1348-1356.

[34] B. C. Mecrow. Fully pitched-winding switched-reluctance and stepping-motor arrangements. *IEE Proceedings B - Electric Power Applications*. 1993. 140(1): 61-70.

[35] A. Zulu, B. C. B. C. Mecrow, M. Armstrong, and A. Zulu. Topologies for wound-field three-phase segmented-rotor flux-switching machines. *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010).* April 19-21. Brighton. 2010. pp. 1-6.

[36] A. Zulu, B. C. Mecrow, and M. Armstrong. A wound-field three-phase flux-switching synchronous motorwith all excitation sources on the stator. *IEEE Transactions on Industry Applications*. 2010. 46(6): 2363-2371.

[37] E. Sulaiman, F. Khan, M. Z. Ahmad, M. Jenal, W. M. Utomo, S. a. Zulkifli, a. a. Bakar, W. M. Utomo, S. a. Zulkifli, and a. a. Bakar. Investigation of field excitation switched flux motor with segmental rotor. *2013 IEEE Conference on Clean Energy and Technology (CEAT)*. November 18-20. Lankgkawi. 2013. pp. 317-322.

[38] Y. J. Zhou, Z. Q. Zhu, and X. Ge. Comparison of torque densities in alternate wound-field switche d flux machines. *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*. October 20-25. Hangzhou. 2014. pp. 2151-2157.

[39] M. Mubin, A. Mazlan, E. Sulaiman, and Z. Ahmad. Design optimization of single-phase outer-rotor hybrid excitation flux switching motor for electric vehicles. *2014 IEEE Student Conference on Research and Development (SCOReD)*. December 16-17 Batu Ferringhi. 2014. pp. 1-6.

[40] N. A. Jafar and E. Sulaiman. Design analysis of 12s-10p hybrid-excitation flux-switching permanent-magnet machines for hybrid electric vehicle. *2014 IEEE 8th International on Power Engineering and Optimization Conference (PEOCO)*. March 24-25. Langkawi. 2014. pp. 308-312.

[41] H. Gamo. A General Formulation of Faraday's Law of Induction. *Proceedings of the IEEE*. 1979. 67(4): 676-677.

[42] A. G. Mikerov. From history of electrical engineering iii : Electromagnetism discovery and its fundamental laws in the first half of 19-th century. *Proceedings of the 2014 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference (ElConRusNW)*. Feb 3-5. St. Petersburg. 2014. pp. 1-7.

[43] Y. Zhao, Y. Wen, Y. Li, Q. Wang, and X. Guo. Modeling and simulation of a permanent magnetic spherical motor based on solidworks and ADAMS. *2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*. Jun 15-17. Auckland. 2015, pp. 1862-1866.

[44] A. Dupas, S. Hlioui, E. Hoang, M. Gabsi, and M. Lecrivain. Investigation of a new topology of hybrid-excited flux-switching machine with static global winding: experiments and modeling. *IEEE Transactions on Industry Applications*. 2016. *52(2): 1413-1421.*

[45] M. Z. Ahmad, E. Sulaiman, Z. a. Haron, and T. Kosaka. Preliminary studies on a new outer-rotor permanent magnet flux switching machine with hybrid excitation flux for direct drive EV applications. *2012 IEEE International Conference on Power and Energy (PECon)*. December 2-5. Kota Kinabalu. 2012. pp. 928-933.

[46] M. Namikawa. Magnetic properties of 6.5% silicon steel sheets under PWM voltage excitation. *1998 The 7th Joint Abstracts MMM-Intermag Conference.* June 6-9. San Francisco. 1998. pp. 141.

[47] S. Zirka, Y. Moroz, P. Marketos, A. Moses, and D. Jiles. Measurement and modeling study of B-H loops and losses of high silicon non oriented steels. *2006 IEEE International Magnetics Conference (INTERMAG)*. May 8-12. San Diego. 2006. pp. 660.

[48] K. Honma, T. Nozawa, H. Kobayashi, Y. Shimoyama, I. Tachino, K. Miyoshi, H. Kobayashi, Y. Shimoyama, I. Tachino, and K. Miyoshi. Development of non-oriented and grain-oriented silicon steel. *IEEE Transactions on Magnetics*. 1985. 21(5): 1903-1908.

[49] X. Ding and C. Mi. Modeling of eddy current loss and temperature of the magnets in permanent magnet machines. *Journal of Circuits, Systems and Computers*. 2011. 20(7): 1287–1301, 2011.

[50] M. Rezal. Rotating analysis of 18-slot/16-pole permanent magnet synchronous motor for light electric vehicle using fem. *2012 IEEE International Conference on Power and Energy (PECon)*. December 2-5. Kota Kinabalu. 2012. pp. 946-949.

[51] S. J. Galioto, P. B. Reddy, A. M. El-Refaie, and J. P. Alexander. Effect of magnet types on performance of high-speed spoke interior-permanent-magnet machines designed for traction applications. *IEEE Transactions on Industry Applications*. 2015. 51(3): pp. 2148-2160.

[52] L. Hao, M. Lin, X. Zhao, and H. Luo. Analysis and optimization of EMF waveform of a novel axial field flux-switching permanent magnet machine. *2011 International Conference on Electrical Machines and Systems (ICEMS)*. August 20-23. Beijing. 2011. pp. 1-6.

[53] G. Dajaku and D. Gerling. A novel 12-teeth/10-poles PM machine with flux barriers in stator yoke. *2012 XXth International Conference on Electrical Machines (ICEM).* September 2-5. Marseille. 2012. pp. 36-40.

[54] X. Liu, Z. Q. Zhu, M. Al-Ani, and B. Lee. Comparative study of the electromagnetic performance of switched flux permanent magnet machines. *IET Electric Power Applications*. 2015. 9(4): 297-306.

[55] N. Pothi and Z. Q. Zhu. A new control strategy for hybrid-excited switched-flux permanent magnet machines without the requirement of machine parameters. *2014 7th IET International Conference on Power Electronics, Machines and Drives (PEMD)*. April 8-10. Manchester. 2014. pp. 1-6.

[56] J. T. Shi, Z. Q. Zhu, D. Wu, and X. Liu. Comparative study of novel synchronous machines having permanent magnets in stator poles. *2014 International Conference on Electrical Machines (ICEM)*. September 2-5. Berlin. 2014. pp. 429-435.

[57] J. T. Chen, Z. Q. Zhu, S. Iwasaki, and R. P. Deodhar. A novel e-core switched-flux pm brushless ac machine. *IEEE Transactions on Industry Applications*. 2011. 47(3): 1273-1282.

[58] S. Yang, J. Zhang, and J. Jiang. A maximum torque control strategy for wound-field flux switching motor drives. *2015 41st Annual Conference of the IEEE on Industrial Electronics Society (IECON)*. November 9-12. Yokohama. 2015. pp. 807-810.

[59] M. A. Ackim Zulu, Barrie Mecrow. A wound-field three-phase flux-switching synchronous motor with all excitation sources on the stator. *2009 IEEE Energy Conversion Congress and Exposition (ECCE)*. Septemeber 20-24. San Jose. 2009. pp. 1502-1509.

[60] Z. Q. Zhu, Y. J. Zhou, and J. T. Chen. Electromagnetic performance of nonoverlapping stator wound field synchronous machine with salient pole rotor. *IEEE Transactions on Magnetics*. 2015. 51(11): 1-4.

[61] E. Sulaiman, T. Kosaka, and N. Matsui. A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle applications. *2011 International Conference on Electrical Machines and Systems (ICEMS)*. August 20-23. Beijing. 2011. pp. 1-6.

[62] Z. A. Husin, E. Sulaiman, and T. Kosaka. Design Studies and Effect of Various Rotor Pole Number of Field Excitation Flux Switching Motor For Hybrid Electric Vehicle Applications. *2014 IEEE 8th International on Power Engineering and Optimization Conference (PEOCO)*. March 20-25. Langkawi. 2014. pp. 144-149.

[63] T. Fan, Q. Li, X. Wen, and S. Member. Development of a High Power Density Motor Made of Amorphous Alloy Cores. *IEEE Transactions on Industrial Electronics*. 2014. 61(9): 4510-4518.