ISSN 2278-3091
Volume 9 No.2, March - April 2020
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse228922020.pdf
https://doi.org/10.30534/ijatcse/2020/228922020

# Flux Switching Machine: Design Variation Review

**Mohd Firdaus Mohd Ab Halim'[1,2], Erwan Sulaiman[1], R. N. F. K. R. Othman[3]**
[1]Research Centre for Applied Electromagnetics, Faculty of Electrical and Electronic Engineering, UniversitiTun Hussein Onn Malaysia Malaysia, erwan@uthm.edu.my
[2]FakultiTeknologiKejuruteraanElektrik&Elektronik, UniversitiTeknikal Malaysia, Malaysia.
mohd.firdaus@utem.edu.my
[3] Centre for Robotics & Industrial Automation, FakultiKejuruteraanElektrik, UniversitiTeknikal Malaysia, Malaysia.
norfirdaus@utem.edu.my

## ABSTRACT

Flux switching machine (FSM) offer advantages such as high torque density, high speed capability, ease of control, low vibration and low acoustic noise compared to competing machine. However, this machine produce high cogging torque, high leakage current and complexity in flux weakening capability design. Many researches focus on tackling these limitations but there is limited review dedicate on the design variation. This paper attempts to review the latest design variation in Permanent Magnet Flux Switching Machine (PMFSM). The review includes slot-rotor pole study, stator structure, rotor structure and special structure with different approach to reduce drawback in PMFSM. This literature review's motivation was to identify areas where the PMFSM need more focus and apply method employ in one structure to another structure to increase the performance of PMFSM. Based on the literature review, 65% of PMFSM design was focus on inner rotor structure while partitioned stator were the least at 11%.

**Keywords**: Flux switching machine, machine design, torque density, torque constant, finite element, electromagnetics

## 1.INTRODUCTION

Flux switching machine (FSM) offer advantages such as high torque density, high speed capability, ease of control, low vibration and low acoustic noise compared to competing machine.FSM is not only capable of delivering mechanical rotation but also can be used as auxiliary power unit or wind generator [1]–[3].Motor that excites on the stator could be the next candidate for electrical vehicle propulsion because it has no active part on the rotor. A comparison between three-phase Double Salient Permanent Magnet Motor (DPSM) and Flux Switching Motor (FSM) yield an advantage towards FSM notably in the phase flux-linkage [4]. FSM is a combination of the switched reluctance motor and the inductor alternator. The first PMFSM motor was introduced in[5] in 1999. The motivation of this invention is to introduce simplicity in motor design and power electronics controller. Besides that, it has the ability to achieve high torque density, flux weakening capability and simple thermal management[6]. In later study [7], due to rapid design evolution in automotive industry, mechanically driven auxiliaries were being substituted by electrically driven equipment for example water pumps, steering system, heating, ventilation and air- conditioning. Brushless dc motor, induction motor and switched reluctance motor were chosen but it comes with a relatively costly power electronic motor drive. Numerous new FSM machine topologies have been developed over the last decade [8], [9]. This machine provides essentially sinusoidal back-EMF and high torque at low speed. Furthermore, it can be used successfully in harsh operating environments, such as aerospace, automotive, marine and wind energy applications[10], [11] parallel to the advancement in energy storage[12], [13]. Many study has categorized this machine into three main classes[14]–[18] based on its excitation source. Permanent magnet flux switching machine (PMFSM), Field Excitation Machine (FEFSM) or Wound Field and Hybrid excitation machine(HEFSM). As the name suggest, the constant field for PMSM is coming from permanent magnet for PMSM, direct current for FEFSM and the combination of both source to create the constant field for HEFSM. This paper attempts to review the latest design variation in Permanent Magnet Flux Switching Machine (PMFSM). The review includes slot-rotor pole study, stator structure, rotor structure and special structure with different approach to reduce drawback in PMFSM. This literature review motivation was to identify areas where the PMFSM need more focus and apply method employ in one structure to another structure to increase the performance of PMFSM.

## 2. PERMANENT MAGNET FLUX SWITCHING MACHINE

### 2.1 Significance of PMFSM

PMFSM is the most studied machine in FSM family mainly because the inclusion of magnet as the field source increases the motor overall efficiency. In general, the performance of any motor with permanent magnet are better because of the reduced volume of winding and its losses. Furthermore, 3mm thick piece of Neodymium Iron Boron (NdFeB) magnets produce magnetic field multiple times higher than similar coil size carrying 10A/mm density [19]. The PMFSM is very similar to the flux reversal machine (FRM or doubly salient permanent magnet (DSPM)[20]–[24]. Based on the comparison between PMFSM and Interior Permanent Magnet machine (IPM) [25], PMFSM has slightly higher torque capability and better flux-weakening capability, when different ratios between stator inner and outer radius are considered. In another study [26], it was shown, that due to the reduced permanent magnet volume, the torque capability and the power capability of the HEFSM decrease, compared to the PMFSM. If the HEFSM is equipped with rare earth magnets, flux strengthening is difficult because of the saturated flux in the iron. To weaken the flux by means of the excitation winding shows less advantages compared to the conventional method, especially because the complexity of the motor increases due to the additional excitation winding, while the power capability decreases compared to the PMFSM Figure 1 illustrate the rectilinear view of flux path in stator -rotor of PMFSM [27].

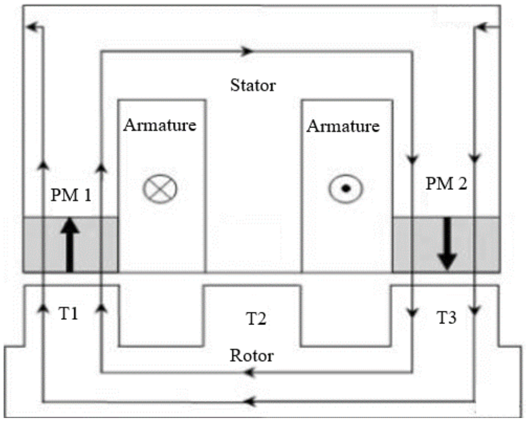


**Figure 1:**Flux path in stator -rotor of PMFSM.

## 2.2 Stator slot –rotor pole ratio

Analysis of the number combinations of stator slot and rotor poles of machine designs should be made in enhancing a machine’s performance. The impact of rotor pole number on the characteristics of single-phase has been presented recently [27]. The result of this study shows that 4S-8P PMFSM structure has registered the highest initial output torque, which produced 2.47Nm, compared with the other three designs namely 2S-8P at 1.45Nm, 8S-12P, and 10S-15P at 1.65Nm and 1.71Nm respectively. Likewise, in similar study [28], 6S-10P PMFSM straight rotor was compared with 6S-8P PMFSM with spanned rotor structure. The result of the study reveals that straight rotor structure yield a higher magnetizing flux concentration compared to the spanned rotor structure. Other stator-rotor combination topologies were also presented in numerous papers [29]–[32]. Odd number of rotor is interesting because could achieve higher back-emf and torque capability versus 12S-10P combination but it has drawback on unbalance magnetic force [33]. Figure 2 illustrate the example of 4S-8P and 2S-8P PMFSM cross-sectional view in stator slot-rotor pole ratio study.

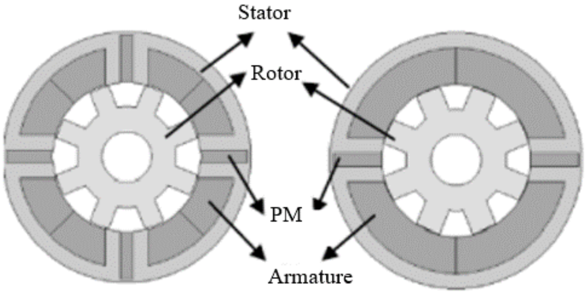


**Figure 2:** PMFSM cross-sectional view in stator slot-rotor pole ratio study (a) 4S-8P (b) 2S-8P.

## 2.3 Rotor structure

In previous year, there was a trend to use in-wheel motors for electric vehicles (EVs) because it offers more passenger space and the possibility of direct wheel control. Outer-rotor structure for PMFSM was first designed in 2010 [34]. More outer-rotor structure was studied and its working principle were validated with finite element software and laboratory experiment applying different stator slot rotor pole ratio and sizes [35]–[43]Figure 3 shows the cross sectional view of outer-rotor structure of PMFSM. Even though this machine offers interesting features, outer rotor structure may be difficult to assemble because it requires overhaul of the wheel system and its control. Furthermore, outer-rotor bearing circumference is larger than inner-rotor which leads to larger friction area besides the difficulty of cooling the inner part of the machine. Meanwhile several topologies were reported in dual-rotor structure of FSM[44]–[47]. To date, research is limited to both rotor rotates in the same direction. A basic dual-rotor structure is similar to inner PMFSM with additional outer-rotor. In general, dual-rotor structure improves the PM utilization hence increases its efficiency. More advance dual-rotor structure employ axial field where the stator were located between two rotors [48]. Axial field PMFSM contributes to shorter axial length, better heat dissipation, and higher torque density [49]. A separate stator may be required to achieve opposite rotation. However, the drawback of dual-rotor is similar to outer-rotor. Furthermore, cogging torque of dual-rotor structure is double as number of rotor interacts with stator field increases. Some advance researchsuggest the use of double rotor structure in co-axial magnetic gear application [50]–[52]. Figure4 illustrates the cross-sectional view of dual-rotor structure of PMFSM.

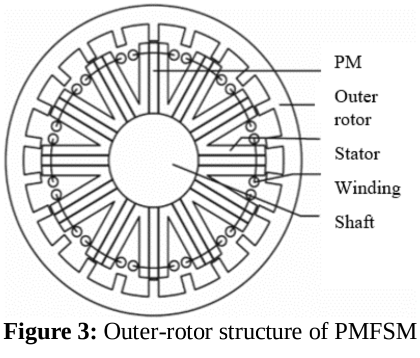


**Figure 3:** Outer-rotor structure of PMFSM

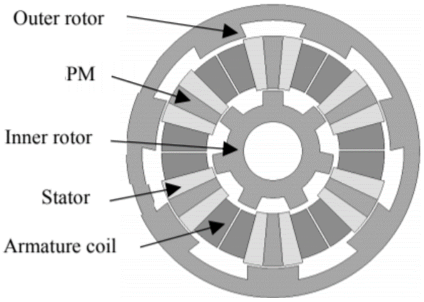


**Figure 4:**Dual-rotor structure of PMFSM

## 2.4 Stator structure

Partition Stator (PS)-PMFSM or dual-stator machine has better torque density due to space utilization of two stators [53]. PM is usually placed at the inner-stator while armature winding is placed at the outer-stator[54]–[56]. Due to larger space at the inner-stator, an equivalent flux performance ferrite magnet can be used to replace rare earth magnet. However, larger motor size limits its application in small space not to mention increase in manufacturing cost as well. Furthermore, stator core losses also will increase in PSPMFSM. Figure 5 illustrates the cross sectional view of structure of PSPMFSM.

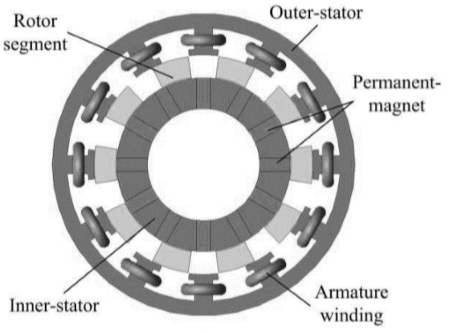


**Figure 5:** Cross-sectional view of dual-stator structure of PMFSM

The advantages of segmental stator specifically as fault tolerance in stator winding such as line-to-line, line-to-ground and three phase faults is presented in [57], [58]. The natural concept of the segmental stator PMFSM are it is made of discontinued section of stator. The gap with an angle α is replaced with non-magnetic material. If an electric fault happened in one of the stator segment, the motor is expected to continue its operation with lower torque.

## 2.5 Design extension and customization

In this section, design extension and customization are reviewed based on its motivation. Segmental rotor proves to be useful in shorten the flux path [59]. Segmental rotor is employed to create bipolar flux linkages in the armature windings and also bipolar flux in the armature tooth for a single cycle of operation[60]. This rotor design is also popular in other type of machine [61]–[64]. The angle 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 based on the number of segments employed. Figure 6 illustrates the cross sectional view of segmental rotor shape (a) 6 pole rotor (b) 8 pole rotor.

Typically, most electrical machine we have today are designed and constructed in order to use the circumferential anisotropic flux distribution including FSM where PM placement is tangential to the shaft. If PM placement is along the stator circumference, then the flux pattern will also change. The combination of both radial and circumferential flux was explored in[65]–[67]. The study discovers that permanent magnet placed located around the back iron and surrounded by a laminated ring frame, could reduce the flux leakage out of the laminated stator core. As of late, there have been many advancements in axial flux machine design [68]–[70]. Axial flux is achieved with double stator or double rotor arrangement where the flux direction is perpendicular to the surface of the rotor and stator. All axial flux studies require 3-D design and analysis which is more time consuming. Furthermore, as the design become more complex, the manufacturability may become more difficult. Figure 7 (a) shows the cross sectional view of the arrangement of the magnet in radial and circumferential setup while Figure 7 (b) illustrate 3D image of axial flux of double stator machine. Unlike the status quo, radial or circumferential flux path, the flux path of axial flux is one-dimensional, allowing the use of grain-oriented magnetic steels for greater efficiency.

Up until this section, the arrangement of the magnet presented is either placed directly from inner side of the stator towards the outer side of the stator and placed along the inner side of stator circumference. Recently, there were attempt to modified the magnet shape resemble to the letter “V”. V-shaped PM is introduced for maximizing output torque and improving magnet utilization. The position of two PM pieces at inner side of the stator remain the same as the conventional PMFSM but the PM position at outer side of the stator is moved closer to shrink low flux density part in lamination and consequently increase the slot area [71]. For outer-rotor structure, the V shaped PM is open towards outside of the machine [72].Likewise, a new stator core shape called multi-tooth machine was designed. It was introduced to further improve the average torque of V-shaped PM. Multi-tooth machine is superior to the V-shaped counterpart, since it exhibits much higher torque to magnet ratio, larger average torque, lower inductance, and much lower UMF, with slight drawback in cogging torque and unfavourable THD [73]. Radially segmented permanent magnets PMFSM was presented in [74].

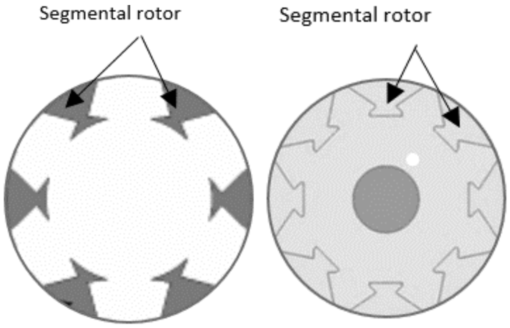
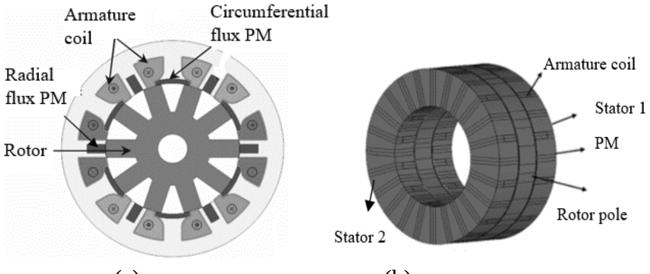


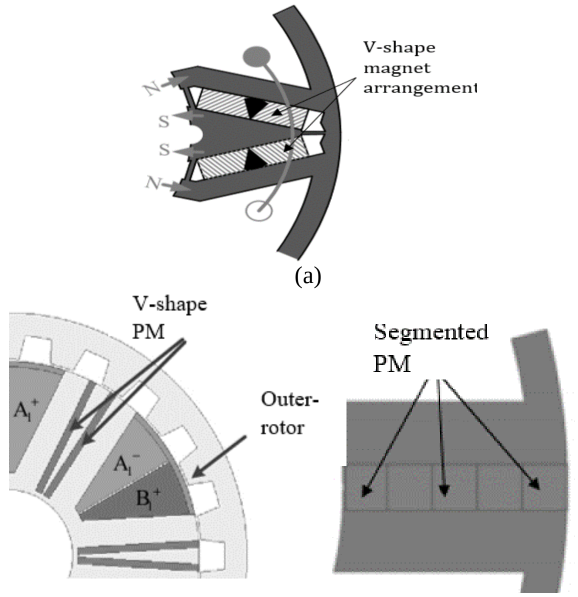
**Figure 6:** Cross-sectional view of segmental rotor shape (a) 6 pole rotor (b) 8 pole rotor



(a) (b)

**Figure 7:**(a) Arrangement of the magnet in radial and circumferential setup (b) Axial flux of double stator machine

The rectangular magnet that is divided into five segment was found to generate slightly higher torque and higher torque to magnet volume ratio. In this design, the higher flux density area near air-gap is placed with smaller PM segment. As the PM location gets further towards the outer surface, the bigger PM segment size is proposed. Figure8 illustrates the V-shape magnet at (a) inner rotor and (b) outer rotor [75]. Figure. 8 (c) shows the cross-sectional view of segmented magnet. Additionally, Figure9illustrate the multi-toothed machine.



(b) (c)

**Figure8:**Cross-sectional view of V-shaped PM (a) inner-rotor, (b) outer-rotor, (c) segmented PM

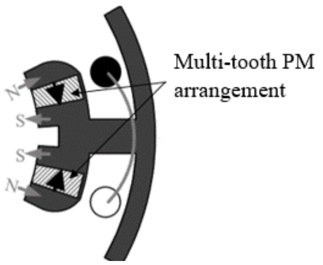


**Figure 9:**Cross-sectional view of multi-toothed machine

Flux Bridges (FB) is a method to minimize the flux leakage out of the stator especially for C-type stator. Flux bridge on the stator teeth can be arrange in 6 ways as depicted in [76], [77]. The results show that C2, C3 and C5 arrangement that is position further away from the stator teeth yield better maximum torque than other arrangement. Besides that, FB is able to mitigate cogging torque and slightly reduce PM length. However, the average torque of the machine is also reduce minimally [78]. A mechanically movable flux adjuster (FA) located on the outside surface of the stator for all or alternative stator poles can improve the flux weakening capability but will increase the motor volume[79], [80]. This method consists of using ferromagnetic pieces located outside the stator to adjust the PM flux level by partially short circuiting the PM flux, and FA can be easily moved by a mechanical system. However, this addition can only apply for inner-rotor FSM. Unlike inserting the mechanical FA onto the outer-stator, the PMFSM partitioned stator machine artfully places the FA within its inner-stator to share the space with the PM. By doing so, the machine size can be kept minimized to improve the power and torque densities. Another design improvement could also be made at the rotor by inserting flux barrier (F-B) in rotor yoke and rotor teeth. This flux barrier could reduce the eddy-current loss by minimizing eddy-current harmonics [81]. Since PMFSM structure is similar to SRM, the new design idea for PMFSM can be inspired by SRM. Cylindrical rotor structure, by implementing ribs connecting each rotor pole is adopted from SRM to reduces windage loss in high-speed operation [82], [83]. The windage loss resulted in the decrease of efficiency in high speed and for low power region in SRM [84]. There were limited design in PMFSM regarding cylindrical rotor structure referred as tubular structure [85], [86]. However, an extensive study was performed for HEFSM that employs two types of cylindrical rotor structure. The windage loss for both design was compared with conventional rotor structure at high speed region about 13,900 rpm. The study found that 35.4% windage loss was reduced in cylindrical rotor structure compares to salient rotor type and slight drawback in maximum torque [87]. Table 1 summarize the design variation, extension and customization of PMFSM. Based on 25 PMFSM design in Table 1, many publications focused on inner rotor while very few in outer rotor, dual rotor and partitioned stator.

**Table 1:** Summary of design variation, extension and customization of PMFSM

| | Design variation | | | | Motivation |
|---|---|---|---|---|---|
| Design extension and customization | Inner-rotor | Outer-rotor | Dual-rotor | Partitioned-stator | |
| Segmental rotor | x | x | x | x | Define flux path |
| Modular rotor | x | | | | Define flux path |
| Circumferential flux | x | x | x | x | Better slot area |
| Radial flux | x | | | | Reduce flux leakage |
| Axial flux | | | x | x | Shorter axial length, better heat dissipation |
| Segmental stator | x | | | | Fault tolerant |
| Stator E, U, C Shape | x | | | | Magnetic circuit arrangement |
| Magnet V inner | x | | | | Improve flux density, magnet utilization |
| Magnet V outer | | x | | | |
| Multi-tooth | x | | | | Upgrade of V-shape |
| Segment magnet | x | | | | Minimize flux leakage at higher flux density area |
| Flux bridge | x | | | | Flux weakening |
| Mechanical flux adjuster | x | | | | Flux weakening |
| Flux adjuster | | x | | | Flux weakening |
| Flux barrier | x | | | | Flux weakening |
| Cylindrical rotor | x | | | | Reduce windage loss at high speed |

## 3. CONCLUSION

In this paper, design variation of PMFSM from recent paper that include slot-pole ratio has been presented thoroughly. Many machine designers choose 12 stator slots as the reference slot number. The ratio of improved topologies is either divided or factorized for example 6S-10 or 24S-14P. Stator slot number must always be even for three phase configuration. There are also researchers study on odd number of rotor pole but this topology suffers greatly at unbalance magnetic force. Complicated structure such as outer-rotor, double stator and double rotor were reviewed as well in this paper. Based on the literature review, 65% of PMFSM design was focus on inner rotor structure while partitioned stator were the least at 11%. There was also lack of radial flux being used in outer rotor, dual rotor and partitioned stator. Future study should apply the design extension and customization that was study extensively in inner rotor to the outer rotor, dual rotor and partitioned stator to identify its feasibility and improve its performance.

## ACKNOWLEDGMENT

The authors would like to thank the Ministry of Higher Education Malaysia, UniversitiTun Hussein Onn Malaysia (UTHM) under Research Fund E15501, Research Management Centre, UTHMand UniversitiTeknikal Malaysia Melaka (UTeM).

## REFERENCES

[1] E. E. M. Mohamed, **“Novel partitioned stator Switched Flux PM machines for wind generator applications,”***2018 Int. Conf. Innov. Trends Comput. Eng. (ITCE), Aswan*, pp. 427–434, 2018. https://doi.org/10.1109/ITCE.2018.8316662

[2] M. Lehr, D. Dietz, and A. Binder, “Electromagnetic design of a permanent magnet Flux-Switching-Machine as a direct-driven 3 MW wind power generator,” in *2018 IEEE International Conference on Industrial Technology (ICIT)*, 2018, pp. 383–388. https://doi.org/10.1109/ICIT.2018.8352208

[3] A. S. Selema, **“Design and Analysis of a Brushless Three Phase Flux Switching Generator for Aircraft Auxiliary Power Unit,”***2018 Twent. Int. Middle East Power Syst. Conf.*, pp. 198–202, 2018.

[4] W. Hua, Z. Q. Zhu, M. Cheng, Y. Pang, and D. Howe, “Comparison of flux-switching and doubly-salient permanent magnet brushless machines,” in *ICEMS 2005: Proceedings of the Eighth International Conference on Electrical Machines and Systems*, 2005, pp. 165–170. https://doi.org/10.1109/ICEMS.2005.202506

[5] C. Pollock and M. Wallace, **“Flux switching motor, a DC motor without magnets or brushes,”***Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc.*, vol. 3, pp. 1980–1987, 1999.

[6] N. Fernando, I. U. Nutkani, S. Saha, and M. Niakinezhad, “Flux switching machines: A review on design and applications,” in *2017 20th International Conference on Electrical Machines and Systems, ICEMS 2017*, 2017, pp. 1–6. https://doi.org/10.1109/ICEMS.2017.8056444

[7] C. Pollock *et al.*, **“Flux Switching Motors for**

**Automotive Applications,"** pp. 242–249, 2003.

[8] Hemamalini B, "Design and Analysis Of Flux Switching Motor," Faculty of Electrical Engineering Anna University, 2016.

[9] Z. Q. Zhu, **"Switched flux permanent magnet machines - Innovation continues,"***2011 Int. Conf. Electr. Mach. Syst. ICEMS 2011*, no. c, pp. 1–10, 2011.

[10] S. Kahourzade, A. Mahmoudi, H. W. Ping, and M. N. Uddin, **"A comprehensive review of axial-flux permanent-magnet machines,"***Can. J. Electr. Comput. Eng.*, vol. 37, no. 1, pp. 19–33, 2014.

[11] G. Verez, G. Barakat, and Y. Amara, **"Influence of slots and rotor poles combinations on noise and vibrations of magnetic origins in 'U'-core flux-switching permanent magnet machines,"***Prog. Electromagn. Res. B*, vol. 61, pp. 149–198, 2015. https://doi.org/10.2528/PIERB14100902

[12] V. R. Sayoc, T. K. Dolores, M. C. Lim, L. Sophia, and S. Miguel, **"Role of Battery Energy Storage System in Modern Electric Distribution Networks - A Review,"***Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 8, no. 3, pp. 443–450, 2019. https://doi.org/10.30534/ijatcse/2019/18832019

[13] J. August, M. K. Singla, A. S. Oberoi, and P. Nijhawan, **"Trends so far in Hydrogen Fuel Cell Technology: State of the art,"***Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 8, no. 4, pp. 1146–1155, 2019. https://doi.org/10.30534/ijatcse/2019/23842019

[14] F. Khan, E. Sulaiman, and M. Z. Ahmad, **"Review of Switched Flux Wound-Field Machines Technology,"***IETE Tech. Rev. (Institution Electron. Telecommun. Eng. India)*, vol. 34, no. 4, pp. 343–352, 2017.

[15] L. I. Jusoh, E. Sulaiman, and S. M. N. S. Othman, **"Comparative study of single phase FE, PM and HE flux switching motors,"***2015 IEEE Student Conf. Res. Dev. SCOReD 2015*, vol. 1, no. c, pp. 583–588, 2015. https://doi.org/10.1109/SCORED.2015.7449403

[16] J. A. Rani, E. Sulaiman, M. F. Omar, M. Z. Ahmad, and F. Khan, **"Computational method of rotor stress analysis for various flux switching machine using J-MAG,"***2015 IEEE Student Conf. Res. Dev. SCOReD 2015*, no. c, pp. 721–726, 2015.

[17] 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 Conf. Energy Conversion, CENCON 2015*, pp. 78–83, 2015.

[18] E. Sulaiman, T. Kosaka, and N. Matsui, **"Design and analysis of high-power / high-torque density dual excitation switched- fl ux machine for traction drive in HEVs,"***Renew. Sustain. Energy Rev.*, vol. 34, pp. 517–524, 2014. https://doi.org/10.1016/j.rser.2014.03.030

[19] J. D. Widmer, R. Martin, and M. Kimiabeigi, **"Electric vehicle traction motors without rare earth magnets,"***Sustain. Mater. Technol.*, vol. 3, pp. 7–13, 2015.

[20] **"Rediscovery of permanent magnet flux-switching machines applied in EV/HEVs: Summary of new topologies and control strategies,"***Chinese J. Electr. Eng.*, vol. 2, no. 2, pp. 31–42, 2016.

[21] D. Li, R. Qu, J. Li, W. Xu, and L. Wu, **"Synthesis of flux switching permanent magnet machines,"***IEEE Trans. Energy Convers.*, vol. 31, no. 1, pp. 106–117, 2016.

[22] L. Somesan, E. Padurariu, I. A. Viorel, and L. Szabo, **"Design of a permanent magnet flux-switching machine,"***Proc. 9th Int. Conf. ELEKTRO 2012*, no. MAY, pp. 256–259, 2012.

[23] S. A. N. Ion Boldea, Congxiao Wang, **"Design of a Three-Phase Flux Reversal Machine,"***Electr. Mach. Power Syst.*, vol. 27:8, pp. 849–863, 1999. https://doi.org/10.1080/073135699268885

[24] R. P. Deodhar, S. Andersson, I. Boldea, and T. J. E. Miller, **"The flux-reversal machine: A new brushless doubly-salient permanent-magnet machine,"***IEEE Trans. Ind. Appl.*, vol. 33, no. 4, pp. 925–934, 1997.

[25] Y. Pang, Z. Q. Zhu, D. Howe, S. Iwasaki, R. Deodhar, and A. Pride, **"Comparative study of flux-switching and interior permanent magnet machines,"***Proceeding Int. Conf. Electr. Mach. Syst. ICEMS 2007*, pp. 757–762, 2007.

[26] J. Krenn, R. Krall, and A. Schmid, **"Comparison of torque-speed-characteristic of flux switching machines with permanent magnet excitation and hybrid excitation,"***2014 12th Int. Conf. Actual Probl. Electron. Instrum. Eng. APEIE 2014* **-** *Proc.*, no. 3, pp. 779–784, 2015.

[27] L. I. Jusoh, E. Sulaiman, R. Kumar, F. S. Bahrim, and M. F. Omar, **"Preliminary studies of various rotor pole number for permanent magnet flux switching machines (PMFSM),"***Int. J. Appl. Eng. Res.*, vol. 12, no. 7, pp. 1377–1382, 2017.

[28] M. Jenal, E. Sulaiman, H. A. Soomro, and S. M. N. Syed Othman, **"Primary study of a new permanent magnet flux switching machine over straight and spanned rotor configurations,"***World J. Eng.*, vol. 13, no. 5, pp. 441–446, 2016.

[29] Y. Yao and C. Liu, **"A efficient nine-phase PM flux-switching machine with high torque density and low torque ripple,"***2018 Asia-Pacific Magn. Rec. Conf. APMRC 2018*, pp. 1–2, 2019. https://doi.org/10.1109/APMRC.2018.8601110

[30] L. Shao, W. Hua, and M. Cheng, **"A new 12/11-pole dual three-phase flux-switching permanent magnet machine,"***2015 18th Int. Conf. Electr. Mach. Syst. ICEMS 2015*, pp. 1502–1507, 2016.

[31] L. I. B. Jusoh, E. Sulaiman, R. Kumar, and F. S. Bahrim, **"Design and performance of 8slot-12pole permanent magnet flux switching machines for electric bicycle application,"***Int. J. Power Electron. Drive Syst.*, vol. 8, no. 1, pp. 248–254, 2017.

[32] W. Xu, J. Zhu, Y. Zhang, Y. Guo, and G. Lei, **"New axial laminated-structure flux-switching**

**permanent magnet machine with 6/7 poles,”** *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 2823–2826, 2011.

[33] J. H. Kim, Y. Li, D. Bobba, and B. Sarlioglu, “New perspective to understand winding configurations of even and odd numbers of pole flux-switching permanent magnent machine,” in *2016 IEEE Transportation Electrification Conference and Expo, ITEC 2016*, 2016, pp. 1–6.

[34] Y. Wang, M. J. Jin, J. X. Shen, W. Z. Fei, and P. C. K. Luk, “An outer-rotor flux-switching permanent magnet machine for traction applications,” in *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, 2010, pp. 1723-1730.

[35] W. Z. Fei, J. X. Shen, C. F. Wang, and P. C. K. Luk, **“Design and analysis of a new outer-rotor permanent-magnet flux-switching machine for electric vehicle propulsion,”** *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 30, no. 1, pp. 48–61, 2011.

[36] R. Kumar, E. Sulaiman, H. A. Soomro, S. H. A. Musavi, G. Kumar, and I. A. Sohu, **“Design and Investigation of Outer Rotor Permanent Magnet Flux Switching Machine for Downhole Application,”** *Int. J. Power Electron. Drive Syst.*, vol. 8, no. 1, pp. 231–238, 2017. https://doi.org/10.1109/ICIEECT.2017.7916555

[37] R. Kumar, E. Sulaiman, H. A. Soomro, S. H. A. Musavi, G. Kumar, and I. A. Sohu, **“Electromagnetic analysis of outer rotor permanent magnet flux switching machine for downhole application,”** *ICIEECT 2017 - Int. Conf. Innov. Electr. Eng. Comput. Technol. 2017, Proc.*, 2017.

[38] E. Mbadiwe and E. Sulaiman, **“Flux switching permanent magnet motor using segmented outer rotor structure for electric scooter,”** *Indones. J. Electr. Eng. Comput. Sci.*, vol. 6, no. 2, pp. 379–386, 2017.

[39] E. Sulaiman, G. M. Romalan, and N. W. A. Ghani, **“Design improvement of flux switching permanent magnet using combined local and global method,”** *ICCEREC 2016 - Int. Conf. Control. Electron. Renew. Energy, Commun. 2016, Conf. Proc.*, vol. 1, pp. 214–219, 2017.

[40] M. Ahmad, E. Sulaiman, Z. Haron, F. Khan, and M. Mazlan, **“Analysis of a New Dual Excitation Flux Switching Machine with Outer- Rotor Configuration for Direct Drive EV,”** vol. 695, pp. 787–791, 2015.

[41] E. Bin Sulaiman and A. M. Arab, **“Fundamental Study Of Outer-Rotor Hybrid Excitation Flux Switching Generator For Grid Connected Wind Turbine Applications,”** *2015 IEEE Student Conf. Res. Dev.*, pp. 716–720, 2015. https://doi.org/10.1109/SCORED.2015.7449431

[42] E. I. Mbadiwe and E. Sulaiman, “Improved design of outer rotor machine in PM technology for motor bike drive application,” in *ISCAIE 2018 - 2018 IEEE Symposium on Computer Applications and Industrial Electronics*, 2018.

[43] N. Ahmad, F. Khan, H. Ali, S. Ishaq, and E. Sulaiman, **“Outer rotor wound field flux switching machine for In-wheel direct drive application,”** *IET Electr. Power Appl.*, vol. 13, no. 6, pp. 703–711, 2019.

[44] E. Sulaiman, M. F. Omar, and L. M. Ishak, **“Design of a Hybrid Permanent Magnetic Flux Switching Machine with Compound Rotor Configuration,”** pp. 208–213, 2016. https://doi.org/10.1109/ICCEREC.2016.7814971

[45] M. K. Hassan, E. Sulaiman, G. M. Romalan, and M. F. Omar, **“Flux Analysis of A Novel Dual Rotor Hybrid Excitation Flux Switching Machine ( DRHEFSM ),”** vol. 10, no. 16, pp. 7064–7069, 2015.

[46] Z. Xiang, L. Quan, and X. Zhu, **“A New Partitioned-Rotor Flux-Switching Permanent Magnet Motor with High Torque Density and Improved Magnet Utilization,”** *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1–5, 2016.

[47] M. K. Hassan, E. Sulaiman, G. M. Romalan, M. F. Omar, and M. Jenal, **“12Slot-14pole Dual Rotor Hybrid Excitation Flux Switching Machine ( DR-HEFSM ) Load Analysis,”** pp. 245–249, 2015.

[48] W. Zhao, T. A. Lipo, and B. Il Kwon, **“A novel dual-rotor, axial field, fault-tolerant flux-switching permanent magnet machine with high-torque performance,”** *IEEE Trans. Magn.*, vol. 51, no. 11, pp. 1–4, 2015. https://doi.org/10.1109/TMAG.2015.2445926

[49] J. Rahmani Fard and M. Ardebili, **“Optimal Design and Analysis of the Novel Low Cogging Torque Axial Flux-Switching Permanent-Magnet Motor,”** *Electr. Power Components Syst.*, vol. 46, no. 11–12, pp. 1330–1339, 2018.

[50] Z. Q. Zhu, **“Overview of Novel Magnetically Geared Machines with Partitioned Stators,”** *IET Electr. Power Appl.*, vol. 12, no. 5, pp. 595–604, 2018.

[51] Y. J. Ge, C. Y. Nie, and Q. Xin, **“A three dimensional analytical calculation of the air-gap magnetic field and torque of coaxial magnetic gears,”** *Prog. Electromagn. Res.*, vol. 131, no. August, pp. 391–407, 2012.

[52] C. Liu and K. T. Chau, **“Electromagnetic Design And Analysis Of Double-Rotor Flux-Modulated Permanentmagnet Machines,”** *Prog. Electromagn. Res.*, vol. 131, no. June, pp. 81–97, 2012. https://doi.org/10.2528/PIER12060605

[53] D. J. Evans, Z. Q. Zhu, H. L. Zhan, Z. Z. Wu, and X. Ge, **“Flux-Weakening Control Performance of Partitioned Stator-Switched Flux PM Machines,”** *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2350–2359, 2016.

[54] C. C. Awah *et al.*, **“Comparison of Partitioned Stator Switched Flux Permanent Magnet Machines Having Single- or Double-Layer Windings,”** *IEEE Trans. Magn.*, vol. 52, no. 1, pp. 0–4, 2016.

[55] C. H. T. Lee, J. L. Kirtley, and M. Angle, **“A**

**Partitioned-Stator Flux-Switching Permanent-Magnet Machine with Mechanical Flux Adjusters for Hybrid Electric Vehicles,"***IEEE Trans. Magn.*, vol. 53, no. 11, 2017.

[56] S. Khalidah, M. Z. Ahmad, G. M. Romalan, and M. Z. M. Arap, **"Comparative analysis of double stator permanent magnet flux-switching machines with segmented inner stator and non-segmented inner stator,"***J. Telecommun. Electron. Comput. Eng.*, vol. 10, no. 1–2, pp. 37–41, 2018.

[57] S. Muhammad, N. Syed, N. Lassim, E. I. Mbadiwe, M. F. Omar, and E. Sulaiman, **"Segmental Stator as a Fault Tolerant for 12Slot- 12Pole Switched Flux Permanent Magnet Machine,"***2019 IEEE 10th Control Syst. Grad. Res. Colloq.*, no. August, pp. 32–35, 2019.

[58] S. M. N. Bin Syed Othman, H. A. Soomro, E. I. Mbadiwe, M. F. Bin Omar, and E. Bin Sulaiman, **"Design and analysis of three phase SegSta 12S-12P permanent magnet flux switching machine,"***2019 2nd Int. Conf. Comput. Math. Eng. Technol. iCoMET 2019*, pp. 1–4, 2019.

[59] M. Jenal and E. Sulaiman, **"Comparative study on a new permanent magnet flux switching machine configuration over segmental and salient rotor structure,"***ARPN J. Eng. Appl. Sci.*, vol. 10, no. 19, pp. 8846–8852, 2015.

[60] E. I. Mbadiwe, E. Sulaiman, and F. Khan, **"Consideration of permanent magnet flux switching motor in segmented rotor for in-wheel vehicle propulsion,"***2018 Int. Conf. Comput. Math. Eng. Technol. Inven. Innov. Integr. Socioecon. Dev. iCoMET 2018 - Proc.*, vol. 2018-Janua, pp. 1–6, 2018. https://doi.org/10.1109/ICOMET.2018.8346399

[61] M. F. Omar, E. Sulaiman, H. A. Soomro, L. I. Jusoh, and F. Amin, **"Slot Pole Study of Field Excitation Flux Switching Machines Using Segmental Rotor and Non-Overlap Windings,"***Int. J. Eng. Technol.*, vol. 7, no. 2.23, pp. 459–463, 2018.

[62] M. F. Omar, E. Sulaiman, M. Jenal, R. Kumar, and R. N. Firdaus, **"Magnetic Flux Analysis of a New Field-Excitation Flux Switching Motor Using Segmental Rotor,"***IEEE Trans. Magn.*, vol. 53, no. 11, pp. 10–13, 2017.

[63] S. M. K. Sangdehi, S. E. Abdollahi, and S. A. Gholamian, "A segmented rotor hybrid excited flux switching machine for electric vehicle application," in *8th Power Electronics, Drive Systems and Technologies Conference, PEDSTC 2017*, 2017.

[64] Z. Xu, D. H. Lee, and J. W. Ahn, **"Design and Operation Characteristics of a Novel Switched Reluctance Motor With a Segmental Rotor,"***IEEE Trans. Ind. Appl.*, 2016.

[65] M. Jenal, E. Sulaiman, M. F. Omar, G. M. Romalan, and H. A. Soomro, **"Development of a novel permanent magnet flux switching machine prototype for light weight electric vehicles,"***2015 IEEE Student Conf. Res. Dev. SCOReD 2015*, pp. 739–744, 2015. https://doi.org/10.1109/SCORED.2015.7449436

[66] M. Jenal, E. Sulaiman, and R. Kumar, **"A new switched flux machine employing alternate circumferential and radial flux (AlCiRaF) permanent magnet for light weight EV,"***J. Magn.*, vol. 21, no. 4, pp. 537–543, 2016.

[67] A. R. Dehghanzadeh, V. Behjat, and M. R. Banaei, **"Dynamic modeling of wind turbine based axial flux permanent magnetic synchronous generator connected to the grid with switch reduced converter,"***Ain Shams Eng. J.*, vol. 9, no. 1, pp. 125–135, 2018.

[68] J. Z. P. Juan Sebastián Lasprilla Hincapié, Andresdavid Vargas Sandoval, "Axial Flux Electric Motor," *Military University of New Granada Mechatronics Engineering*, 2019. .

[69] Q. A. S. Syed and I. Hahn, **"Analysis of flux focusing double stator and single rotor axial flux permanent magnet motor,"***IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2016*, vol. 2016-Janua, pp. 1–5, 2017.

[70] W. Zhang, X. Liang, and M. Lin, **"Analysis and Comparison of Axial Field Flux-Switching Permanent Magnet Machines with Three Different Stator Cores,"***IEEE Trans. Appl. Supercond.*, 2016.

[71] Y. J. Zhou and Z. Q. Zhu, **"Torque Density and Magnet Usage Efficiency Enhancement of Sandwiched Switched Flux Permanent Magnet Machines Using V-Shaped Magnets,"***IEEE Trans. Magn.*, vol. 49, no. 7, pp. 3834–3837, 2013. https://doi.org/10.1109/TMAG.2013.2238219

[72] X. Zhu, Z. Shu, L. Quan, Z. Xiang, and X. Pan, **"Multi-Objective Optimization of an Outer-Rotor V-Shaped Permanent Magnet Flux Switching Motor Based on Multi-Level Design Method,"***IEEE Trans. Magn.*, vol. 52, no. 10, pp. 1–8, 2016.

[73] G. Zhao and W. Hua, **"Comparative Study between a Novel Multi-Tooth and a V-Shaped Flux-Switching Permanent Magnet Machines,"***IEEE Trans. Magn.*, vol. 55, no. 7, pp. 1–8, 2019.

[74] M. M. J. Al-Ani and M. L. Jupp, "Switched flux permanent magnet machine with segmanted magnets," in *8th IET Conference Publications*, 2016, vol. 8, no. PEMD2016, pp. 1–5.

[75] Z. Shu, X. Zhu, L. Quan, Y. Du, and C. Liu, **"Electromagnetic performance evaluation of an outer-rotor flux-switching permanent magnet motor based on electrical-thermal two-way coupling method,"***Energies*, 2017.

[76] N. A. Jafar, E. Sulaiman, and S. K. Rahimi, **"Performance Analysis of 12S-10P HEFSM with Various Flux Bridges,"** vol. 774, pp. 781–785, 2015.

[77] N. A. Jafar, E. Sulaiman, and S. K. Rahimi, **"Premilinary Studies of Iron Flux Bridges on Hybrid-Excitation Flux Switching Machine for HEV Applications,"** vol. 9, no. 18, pp. 219–226,

2014.

[78] C. Gan, J. Wu, M. Shen, W. Kong, Y. Hu, and W. Cao, **"Investigation of Short Permanent Magnet and Stator Flux Bridge Effects on Cogging Torque Mitigation in FSPM Machines,"***IEEE Trans. Energy Convers.*, vol. 33, no. 2, pp. 845–855, 2018. https://doi.org/10.1109/TEC.2017.2777468

[79] R. P. Deodhar, A. Pride, S. Iwasaki, and J. J. Bremner, **"Performance improvement in flux-switching PM machines using flux diverters,"***IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 973–978, 2014.

[80] Z. Q. Zhu, M. M. J. Al-Ani, X. Liu, and B. Lee, **"A Mechanical Flux Weakening Method for Switched Flux Permanent Magnet Machines,"***IEEE Trans. Energy Convers.*, vol. 30, pp. 806–815, 2015.

[81] J. Luo, J. Ji, and Y. Zhang, **"Reduction of eddy current loss in flux-switching permanent-magnet machines using rotor magnetic flux barriers,"***2017 IEEE Int. Magn. Conf. INTERMAG 2017*, vol. 53, no. 11, pp. 1–5, 2017. https://doi.org/10.1109/TMAG.2017.2698604

[82] J.-W. Ahn and G. F. L. Lukman, **"Switched Reluctance Motor: Research Trends and Overview,"***China Electrotech. Soc. Trans. Electr. Mach. Syst.*, vol. 2, no. 4, pp. 339–347, 2019.

[83] S. H. Won, J. Choi, and J. Lee, **"Windage Loss Reduction of High-Speed SRM Using Rotor Magnetic Saturation,"** vol. 44, no. 11, pp. 4147–4150, 2008.

[84] K. Kiyota, S. Member, T. Kakishima, and S. Member, **"Cylindrical Rotor Design for Acoustic Noise and Windage Loss Reduction in Switched Reluctance Motor for HEV Applications,"***IEEE Trans. Ind. Appl.*, vol. 52, no. 1, pp. 154–162, 2016.

[85] J. Wang, W. Wang, K. Atallah, and D. Howe, **"Design Considerations for Tubular Flux-Switching Permanent Magnet Machines,"***IEEE Trans. Magn.*, vol. 44, no. 11, pp. 4026–4032, 2008.

[86] Y. Sui, P. Zheng, Y. Liu, M. Wang, and Z. Yin, **"Tubular unified magnetic-field flux-switching PMLM for free-piston energy converter,"***IET Electr. Power Appl.*, vol. 13, no. 5, pp. 625–634, 2019. https://doi.org/10.1049/iet-epa.2018.5217

[87] Y. Okada, T. Kosaka, N. Matsui, and A. M. Structure, **"Windage Loss Reduction for Hybrid Excitation Flux Switching Motors Based on Rotor Structure Design,"***2017 IEEE Int. Electr. Mach. Drives Conf.*, pp. 1–8, 2017. https://doi.org/10.1109/IEMDC.2017.8002360