International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 8, No. 1, March 2017, pp. 231~238
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i1.pp231-238

Design and Investigation of Outer Rotor Permanent Magnet Flux Switching Machine for Downhole Application

Rajesh Kumar[1], Erwan Sulaiman[2], Mahyuzie Jenal[3], Laili Iwani Jusoh[4], Fatihah Shafiqah Bahrim[5]
[1,2,3,4,5] Research Center for Appied Electromagnetics, University of Tun Hussein Onn Malaysia (UTHM)
Locked Bag 101, Parit Raja 86400, Batu Pahat, Johor, Malaysia

Article Info

Article history:

Received Oct 10, 2016
Revised Dec 16, 2016
Accepted Dec 26, 2016

Keyword:

Downhole application
Flux switching
Hight torque
Outer rotor
Permanent magnet

ABSTRACT

Permanent magnet flux switching machine (PMFSM) is a joint venture of switch reluctance machine (SRM) and permanent magnet synchronous machine (PMSM). It has become a prominent research topic for various applications because of robust rotor structure, high torque and power densities but few were developed for downhole applications mainly due to harsh environmental conditions. Formerly, most of developed PMFSMs for downhole applications were mainly concentrated on inner-rotor type design, and difficult to find research work on outer-rotor configuration. Therefore, this paper introduces the design and investigation of PMFSM with outer-rotor configuration for downhole application. Primarily, the geometric topology of proposed design is described in detail. Then, the no load and load analysis are implemented in order to investigate the initial performance of the proposed design.

Corresponding Author:

Erwan Sulaiman,
Research Center for Appied Electromagnetics,
University of Tun Hussein Onn Malaysia (UTHM),
Locked Bag 101, Parit Raja 86400, Batu Pahat, Johor, Malaysia.
Email: erwan@uthm.edu.my

1. INTRODUCTION

Induction motors have been widely employed in downhole application to drive submersible pumps because they are robust, cost effective and easy to maintain [1]. However, they are incompetent to fulfill the requirements of higher power densities, higher efficiencies and better controllability when compared with permanent magnet synchronous machines as shown in Table 1. [2]. In spite of these advantages, few were designed for downhole application because of high ambient temperatures in deep reservoirs and low temperature stability of permanent magnet materials which creates demagnetization effects in machine operation [3].

Recent advancement in permanent magnet (PM) technologies permits operation at higher temperatures without permanent magnetization loss [4]. Therefore, it is increasingly interesting opportunity for oil and gas sectors to develop permanent magnet machines for downhole application.

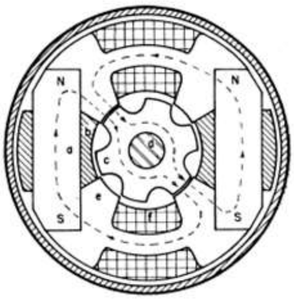
The permanent magnet flux switching machine is an unfamiliar type of PM machines comprising a passive and robust salient pole rotor and complex salient pole stator with armature winding and permanent magnets. The first PMFSM was presented as a single phase alternator in 1955 shown in Figure 1(a), employing low performance magnet material [5], while Figure 1(b) depicts a three phase brushless machine was first presented in 1997 [6]. Contemporary, there have been renewed research interest PMFSM, apparently due to a number of perceived benefits. Since all active parts such as permanent magnet and armature windings are all placed on the stator, simple yet efficient machine. Thus, cooling can be easily implemented [7]. Furthermore, additional advantages such as robust rotor structure, high torque and flux densities, high efficiency and better flux weakening ability are comprehensively examined and verified for number of applications [8]-[10].

Placing the rotor on the outer surface will generate more torque, compared to the conventional inner rotor [11]. However, research on the PMFSM has mainly focused on the electromagnetic analysis and optimization of the inner rotor type [12]-[14], with barely paid any attention to the outer rotor PMFSM. Recently, few outer rotor PMFSMs were developed especially for light tractions applications [15]-[16].

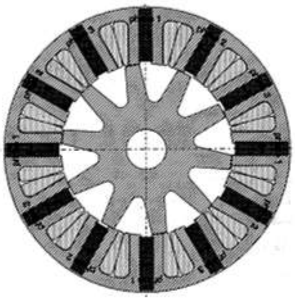
This paper mainly focuses on the design and investigation of outer rotor PMFSM for downhole application. In Section 2, firstly the machine design technique is introduced. Then, the relationships between different machine parameters are developed. In Section 3 outer rotor PMFSM is analyzed under no load condition such as flux linkage, cogging torque, and back electromotive force (EMF). Finally, the load analysis is carried out in Section 4.

Table 1. Performance comparision [2]

Performance	Induction Motor	PMSM
Power Density	Neutral	Very Good
Effeciency	Good	Very Good
Reliability	Very Good	Neutral
Technical Maturity	Good	Neutral
Controllability	Neutral	Good



(a)



(b)

Figure 1. (a) Single phase alternator (b) Three phase brushless machine

2. GEOMETRIC TOPOLOGY

The outer rotor PMFSM has doubly salient structure with a novel topology. The flux switching theory for electric machine originates from variation of both amplitude and polarity of flux linkages in the armature winding in accordance with rotor position. Figure 2(a), shows cross sectional view of outer rotor PMFSM. Each stator slot consists of two iron teeth and a rectangular permanent magnet sandwiched between them, and grasped by concentrated armature windings, while rotor pole is simply formed with an iron tooth.

The key design parameters of outer rotor PMFSM are bounded by geometric relationship are construed in a magnified local structure as shown in Figure 2(b). The stator slot should be even multiple of phase numbers. Thus, the relationship between stator slot number and N_s rotor pole number N_r is [17].

$$Nr = \frac{(12 \pm n) * Ns}{6} \tag{1}$$

Where n is an integer (positive) which should not be a multiple of three. To obtain zero resultant magnetic force, N_r is chosen to be an even number. The key design parameters such as stator tooth width arc β_s, rotor pole width arc β_r permanent magnet width arc β_{pm} and stator armature slot width arc β_{slot} initially set as

$$\beta r = \beta s = \beta pm = \frac{\beta slot}{3} = \frac{\pi}{3Ns} \tag{2}$$

On the other hand, additional relationship between stator inner radius R_{si}, and outer radius R_{so}, stator back length h_{ys} and rotor yoke length h_{yr} are originally fixed as

$$Rsi = \frac{Rso}{2} \tag{3}$$

$$hyr = 1.5 * hys \tag{4}$$

Additionally, to obtain sufficient rotor saliency, the rotor pole height h_{pr} is set as

$$hpr = \frac{Rso}{8} \tag{5}$$

Moreover, stator slot winding area Aslot can be determined as

$$Aslot = \frac{Rso^2 \sin\left(\frac{\pi}{2Ns}\right)^2}{2\tan\left(\frac{\pi}{Ns}\right)} \tag{6}$$

In addition, number of turns N_a for one stator slot and peak injected current I_m in each coil can be calculated as

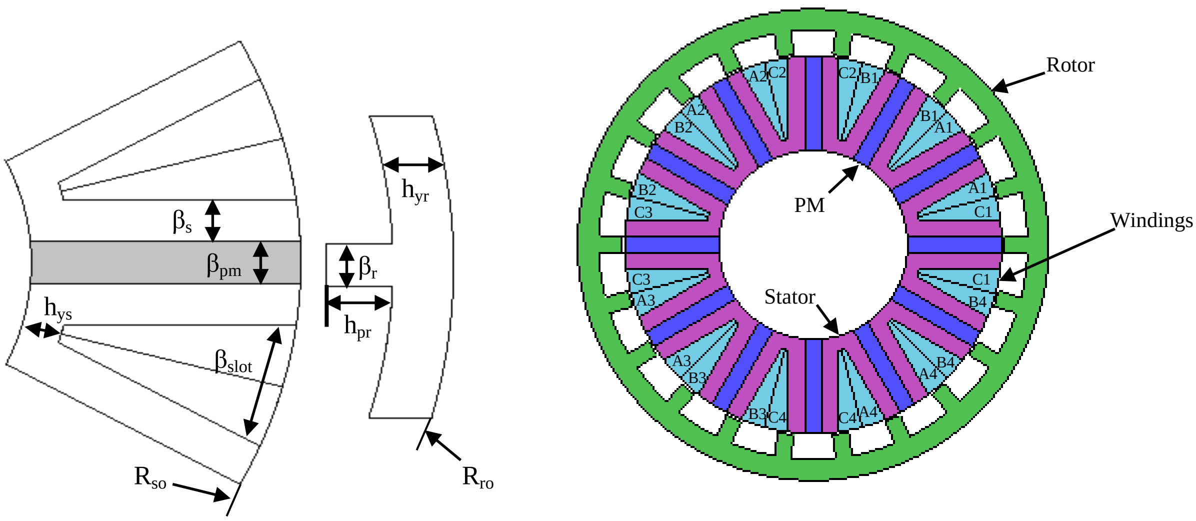
$$Na = \frac{2Aslot * \alpha}{\pi d^2} \tag{7}$$

$$I_m = \frac{Ja * Aslot * \alpha}{2Na} \tag{8}$$

Where, α is filling factor, d is the diameter of wire and J_a is the peak injected current density. Finally, the rotor outer radius can be derived as

$$Rro = \left(\frac{9}{8} + \frac{\pi}{2Ns}\right) * Rso + g \tag{9}$$

Where, g is the air gap. Table 2, shows key geometric parameters of outer rotor PMFSM that are calculated through above mentioned equations.



(a) (b)

Figure 2. (a) Key design parameteres (b) Cross sectional view

Table 2. Design specification of outer rotor PMFSM

Parameters	Abbreviation	Value	Units
Stator Slot Number	Ns	12	
Rotor Pole Number	Nr	22	
Rotor Outer Radius	Rro	50	mm
Rotor Inner Radius	Rri	40.5	mm
Stator Inner Radius	Rsi	20	mm
Stator Outer Radius	Rso	40	mm
Stator Back Length	hys	3	mm
Rotor Yoke Length	hyr	4.5	mm
Rotor Pole Width	β_r	3.49	mm
Stator Tooth Width	β_s	3.49	mm
Permanent Magnet Width	β_{pm}	3.49	mm
Slot Area	Aslot	50.732	mm^2
Air Gap	g	0.5	mm
Stack Length	l	200	mm
Number of Turns	Na	33	
Synchronous Speed	ω	1000	rpm
Armature Current Density	Ja	30	A/mm^2
Split Ratio	λ	0.8	

3. OPEN CIRCUIT ANALYSIS

This section includes comprehensive discussion of outer rotor PMFSM for downhole application under no load condition such as coil test arragement, flux line and distribution, cogging torque and induced voltages.

3.1. Operating Principle

The principle of operation for outer rotor PMFSM for downhole application is verified by coil test arrangement. In a balanced three phase (3∅) system, the three phases of 12 armature coils are determined by inspecting the magnetic flux linkage on each of armature coil. The armature current density was set at $0A/mm^2$ so that the total flux is generated by PM only. Therefore, by revolving the rotor at the speed of 1000r/min, the flux linkage on armature coils is shown in Table 3.

The 3∅ flux linkage is plotted in Figure 3, when the polarity and phase of the entire armature coil has been diagnosed. From the figure, it can be observed that the resulting amplitude of the PM generated flux is about 0.09Wb that is sufficient for motor operation. Apart from this it has almost sinusoidal waveform.

Table 3. Phase representation of armature coil

Phase	Armature Coil
U	A1, A2, A3, A4
V	B1, B2, B3, B4
W	C1, C2, C3, C4

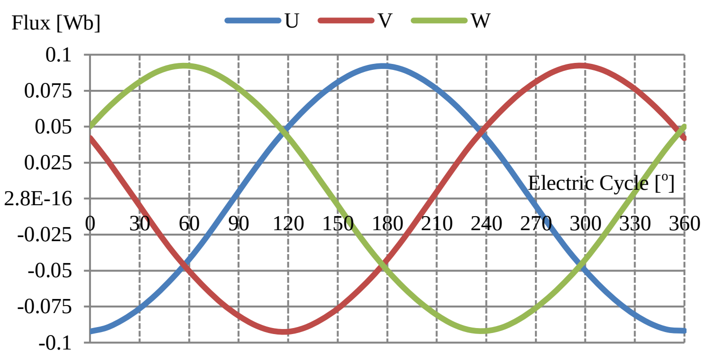


Figure 3. Three phase flux linkage

3.2. Cogging Torque

It is also called as detent or 'no-current' torque that creates noise and vibration in machine operation. The PM generated cogging torque analysis for one electrical cycle is shown in Figure 4. The cogging torque waveform has 6 numbers of cycles that are calculated as [18].

$$N_p = \frac{N_r}{HCF[N_r N_s]} \tag{10}$$

$$N_e = \frac{N_p N_s}{N_r} \tag{11}$$

Where, *HCF* is the highest common factor, N_p is the constant and N_e is the number of cogging torque cycles. Moreover, it is observed from the graph that the peak to peak cogging torque is about 3.2Nm. This simulated design has low cogging torque which is desirable for machine operation.

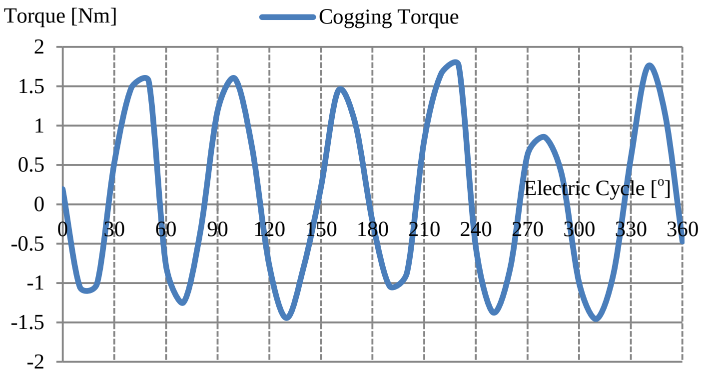
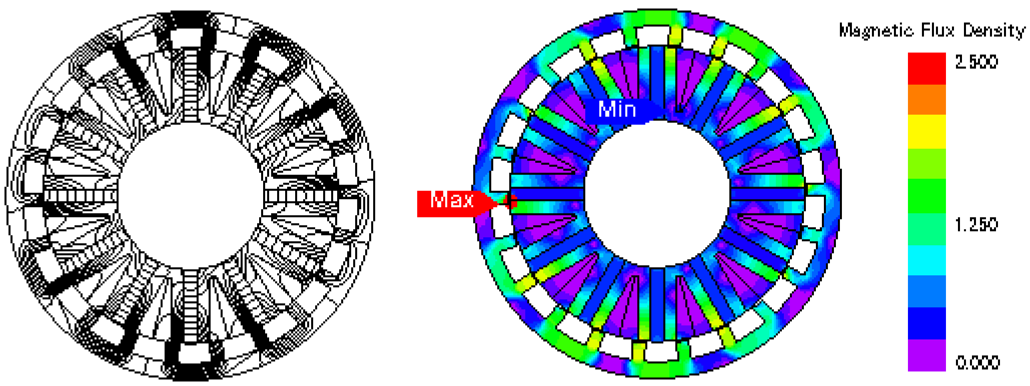


Figure 4. Cogging torque waveform

3.3. Flux Lines and Distribution

The purpose of flux lines is to monitor the flow of flux, while flux distribution reflects the effect of flux saturation in the machine. Figure 5(a) depicts that, the flux lines travel from stator teeth to rotor pole and rebound back from nearest rotor pole, in order to make full cycles. Apparently, the initial design has more flux leakage, which distorts the flux flow from stator core to rotor and vice versa. Furthermore, the maximum flux density of 2.36T value measured in Figure 5(b).



(a) (b)

Figure 5. (a) Flux Lines (b) Flux Distribution

3.4. Induced Voltages

Further examination of the propective design on back EMF in no load condition is carried out at the speed of 1000 r/m. The results obtained for back-emf are plotted in Figure 6. Initially, line and phase voltages of the proposed design are approximately 355.4V and 205.2V respectively. The high values of back EMF can be further reduced using design rectification methods. Howerver, it has favorable sinusoidal waveform due less harmonic distortion.

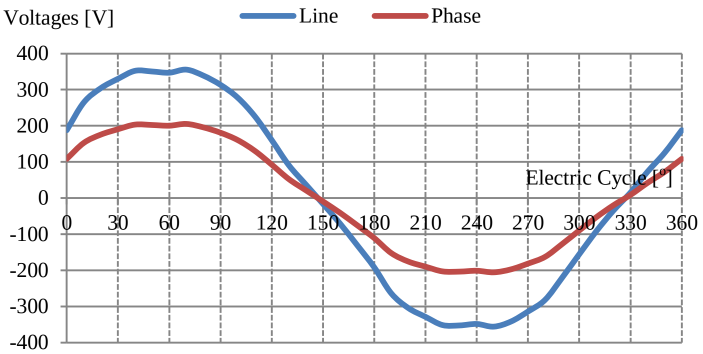


Figure 6. Induced voltages of 12s-22p

4. CLOSED CIRCUIT ANALYSIS

This section covers load investigation of outer rotor PMFSM for downhole application which includes torques at various armature current densties, torque and power versus speed.

4.1. Average Output Torque versus Armature Current Densities

The average electromagnetic torque of proposed design can be calculated as

$$T_{avg} = \frac{\pi}{8} N_r K_d B_g J_a A_{slot} R_{so} l\alpha \tag{12}$$

Where B_g air gap flux density at no load contdition, K_d is leakage factor which is taken as 0.75. The obtained results from calculation and simulation are plotted in Figure 7, in which armature current density is varied from 0A/mm^2 to 30A/mm^2. The maximum simulated and calculatd torque of 75.30Nm and 93.09Nm respectively are obtained at 30A/mm^2, for downhole application the armature current density is kept at 5A/mm^2 and average output torque through simulation and calculation are found to be 16.39Nm and 15.51Nm respectively.

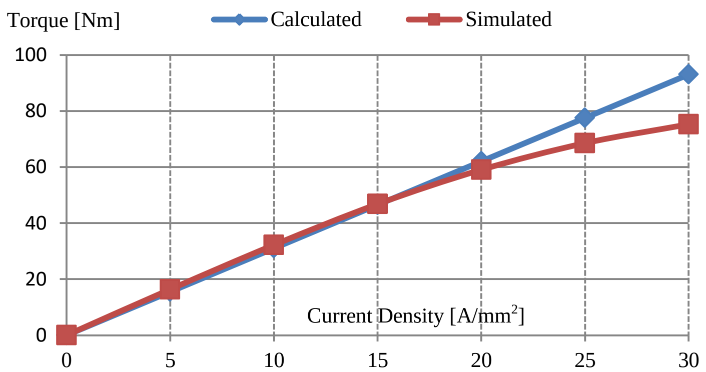


Figure 7. Average torque at various armature current densities

4.2. Torque and Power versus Speed Characteristics

For proposed outer rotor PMFSM, the torque and power versus speed curve is ploted in Figure 8. The solid blue line indicates the torque-speed curve, while red line represents the power curve. For proposed design, at base speed 1108.1rpm, the torque obtained is 75.03Nm while corresponding maximum power obtained from preliminary design is 8.73kW.

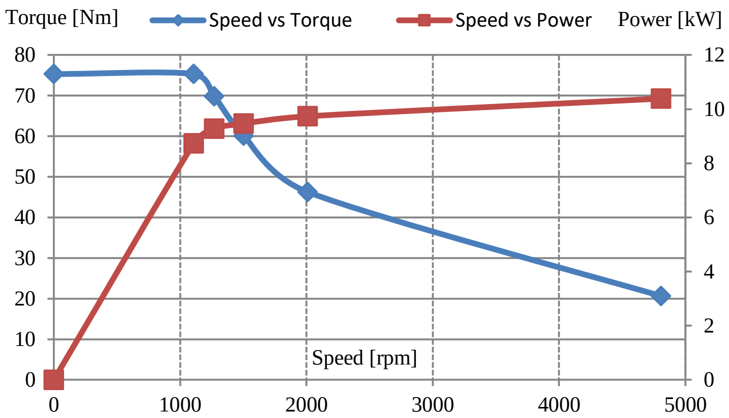


Figure 8. Torque – power against speed curve

5. CONCLUSION

In this research paper, design and analysis of outer rotor PMFSM for downhole application has been introduced. Firstly, design procedure for proposed machine has been described comprehensively. Then, the no load and load tests were executed in order to observe the initial performance of the machine. From the results that have been obtained, it can be concluded that the initial performance of the machine can further be improved through design refinement and optimization process.

ACKNOWLEDGEMENTS

This research work was supported by Research, Innovation, Commercialization and Consultancy (ORICC) UTHM, Batu Pahat under Vot number U519 and Ministry of Higher Education Malaysia (MOHE).

REFERENCES

[1] A. Chen, *et al.*, “Review of Electrical Machines in Downhole Application and Their Advantages,” *13th International Power Electronics and Motion Conference*, Poznan, Poland, 2008.
[2] A. Chen, *et al.*, “Investigation of a Three Phase Flux Switching Permanent Magnet Machine for Downhole Applications,” *20th International Conference on Electrical Machines*, Rome, 2010.
[3] T. Finken and K. Hameyer, “Design of Electric Motors for Hybrid Electric Vechile Applications,” *ICEMS 2009*, Tokyo, Japan, Nov 15-18, 2009.
[4] M. J. Melfi, *et al.*, “Induction versus permanent magnet motors,” *IEEE Industrial Application Magazine*, 2009.
[5] S. E. Rauch and L. J. Johnson, “Design Principle of Flux Switching Alternators,” *IEEE Transaction on Power Applications Systems III*, vol/issue: 74(3), pp. 1261-1268, 1955.
[6] E. Hoang, “Switching Flux PM Polyphased Synchronous Machines,” *7th European Conference on Power Electronics Applications*, vol. 3, pp. 903-908, 1997.
[7] Z. Q. Zhu, *et al.*, “Analysis of Eectromagnetic Performance of Flux Switching PM Machine by Non-Linear Adaptive Lumped Parameter Magnetic Circuit Model,” *IEEE Transaction on Magnetics*, vol/issue: 41(11), 2005.
[8] E. B. Sulaiman and T. Kosaka, “Development of High Torque and High Power Density Hybrid Excitation Flux Switching Motor for Traction Drive in Hybrid Electric Vehicles,” *Energy and Power Engineering*, 2013.
[9] C. S. Walter, *et al.*, “High Torque Density High Efficiency Flux Switching Machine for Aerospace Applications,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol/issue: 1(4), pp. 327-336, 2013.
[10] Z. Q. Zhu, *et al.*, “Analysis of a Novel Multi Tooth Flux Switching PM Brushless AC Machine for High Torque Direct Drive Applications,” *IEEE Transaction for Magnetics*, vol/issue: 44(11), pp.4313-4316, 2008.
[11] C. V. Aravind, *et al.*, “Double Rotor Switched Reluctance Motors: Fundamentals and Magnetic Circuit Analysis”. *IEEE SCORED*, Kualalumpur, Malaysia, pp. 294-299, 2011.
[12] T. Raminosoa, *et al.*, “Design Consideration for a Fault Tolerant Flux Switching Permanent Magnet Machine,” *IEEE transaction on Industrial Electronics*, vol/issue: 58(7), pp. 2818-2825, 2010.

[13] M. Cheng, *et al*, "Nonlinear Varying Network Magnetic Circuit Analysis for Doubly Salient Permanent Magnet Motors," *IEEE Transactions on Magnetics*, vol. 36, pp. 339-348, 2000.
[14] R. L. Owen, *et al*., "Alternate Poles Wound Flux-Switching Permanent-Magnet Brushless AC Machines," *IEEE Transactions on Industrial Applications*, vol/issue: 46(2), pp 790-797, 2010.
[15] Y. Wang, *et al*., "An Outer Rotor Flux-Switching Permanent Magnet Machine for Traction Applications," *IEEE Energy Conversion Congress and Exposition*, pp. 1723 – 1730, 2010.
[16] W. Fei, *et al*., "A Novel Permanent Magnet Flux Switching Machine for Urban Electric Vehicle Propulsion," *3rd International Conference on Power Electronics System and Applications*, 2009.
[17] W. Fei, *et al*., "A Novel Permanent Magnet Flux Switching Machine with an Outer Rotor Configuration for in Wheel Light Traction Applications," *IEEE Transaction on Industry Applications*, vol. 48, pp. 1496-1506, 2012.
[18] M. Wallace, "The New Flux Switching Motor – A DC Motor without Brushes," *Ph.D Thesis*, University of Warwick, Poland, 2000.

BIOGRAPHIES OF AUTHORS

Rajesh Kumar was born on 3rd September 1992 at Umerkot, Pakistan. He obtained his intermediate education from his hometown while he received B.E in industrial electronics from Institute of Industrial Electronics Engineering, Karachi, Pakistan in 2013. He is currently enrolled in M.E at Department of Electrical Power Engineering, University Tun Hussein Onn Malaysia. His research intentions are mainly focused on design and modeling of permanent magnet flux switching machines (PMFSMs).

Erwan Sulaiman was born in Johor, Malaysia, on August 31, 1978. He received his B.E and M.E degrees in Electrical Engineering from University of Malaya in 2001 and University Tun Hussein Onn Malaysia (UTHM) in 2004. He got Doctor Degree in Electrical Engineering from Nagoya Institute of Technology (NIT), Japan in 2012. Currently, he is serving as an associatate professor at Department of Electrical Power Engineering, University Tun Hussein Onn Malaysia. His research interests incorporate design optimizations of HEFSM, WFFSM, in particular, for HEV drive applications.

Mahyuzie Jenal got his birth in Johor, Malaysia, on December 4, 1977. He got his B.E and M.E degrees in Electrical Engineering from Universiti Teknologi Malaysia in 2000 and Universiti Tun Hussein Onn Malaysia (UTHM) in 2009. He has been with UTHM from June 2003 as instructor and selected as a lecturer in 2009. He is currently PhD candidate at Universiti Tun Hussein Onn Malaysia. His research interest is electric machine design especially in permanent magnet flux switching machine.

Laili Iwani binti Jusoh was born in Besut, Terengganu, Malaysia, on August 2, 1987. She achieved her B.E degree in Electrical Engineering form University of Tun Hussein Onn Malaysia in 2010. After that, she obtained Master in Technical Vocational and Education from UTHM in 2014. Currently, she is pursuing Ph.D at UTHM. Her research targets are mainly related to single and three phase permanent magnet flux switching machines for light electric vehicles.

Fatihah Shafiqah Bahrim was born in Johor, Malaysia on November 1992. She received the B.S. degree in electrical engineering from Universiti Teknologi Mara (UiTM), Selangor, Malaysia in 2015. Since September 2015, she has been a researcher in Research Center for Applied Electromagnetics (EMC) at Universiti Tun Hussein Onn, Johor, Malaysia. Her present research interests include design and modelling of electrical machine, special electrical machine and embedded power electronics.