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# Impact of Rotor Pole Number on the Characteristics of Outer-Rotor Hybrid Excitation Flux Switching Motor for In-Wheel Drive EV

M.Z. Ahmad[a]*, E. Sulaiman[a], Z.A. Haron[a], T. Kosaka[b]

[a]*Faculty of Electrical & Electronic Eng., Universiti Tun Hussein Onn Malaysia, Bt. Pahat, 86400, Johor, MALAYSIA*
[b]*Dept. of Electrical and Computer Engineering, Nagoya Institute of Technology (NIT), Nagoya, JAPAN*

**Abstract**

This paper present the impact of rotor pole number on the characteristics of outer-rotor hybrid excitation flux switching motor (ORHEFSM) for in-wheel drive electric vehicle (EV) applications. In recent years, researches on in-wheel motor for EV drivetrain system become more popular due to their several advantages of independent wheel controllability and higher efficiency. In addition, it provides more cabin space caused by elimination of mechanical transmission gears as conventionally use in the most of existing EV with single motor propulsion system configuration. Moreover, the proposed motor has single piece of rotor making the motor more robust and suitable for high speed applications. Under some design restrictions and specifications, design principles and initial performances of the proposed motor at various rotor pole numbers with 12 stator slots are demonstrated. Initially, the coil arrangement tests are examined to confirm the operating principle and polarity of each armature coil phase of the proposed motor. Furthermore, the profile of flux linkage, induced voltage, cogging torque and torque characteristics at various field excitation current density conditions are analyzed based on 2D- finite element analysis (FEA). The results obtained show that the appropriate combination of stator slot-rotor pole configurations are 12S-10P which initially provide highest torque and power density. Thus, by further design refinement and optimization it is expected that the motor will successfully achieved the target performances.

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*Keywords*: Outer-rotor hybrid excitation flux switching motor; field excitation coil; electric vehicle propulsion; in-wheel drive

* Corresponding author. Tel.: +607-4537502; fax: +607-4536060.
*E-mail address:* zarafi@uthm.edu.my

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## 1. Introduction

Since several decades ago, all around the world are facing of global warming issues and among the factor that contributes on this phenomenon is the increasing use of personal vehicles. The conventional internal combustion engine (ICE) vehicles are the main contributors on this issue. By 2050, it is expected that the emissions from cars and vans in which the conventional ICE based vehicles contributes up to 14% from the total of $CO_2$ emissions [1]. Thus, the battery-powered electric vehicles (BEVs) seem like the only a solution in reducing the energy crisis and global warming due to advantages of zero oil consumption and zero emissions. Therefore, Electric Vehicle (EV) now is looks as an alternative eco-friendly car and becomes popular in the very near future [2].Research and development efforts have focused on developing advanced powertrains and efficient energy systems. The most basic characteristics requirements of an electric motor for EV drive system are high torque and power density and constant power at high speed as well as high efficiency [3].

Basically, there are two class of EV drivetrain system. First is centralized motor drive with reduction and a differential gear. Whilst, second is in-wheel direct drives with independent power electronics control system. However, till right now the centralized drive appears to be more popular partly due to its similarity with existing ICE based system. The in-wheel direct drive configuration is gaining popularity as a more electric motor based system that offers potential superior features. In addition, due to the elimination of mechanical transmission, differential gears and drive belts, the in-wheel direct drivetrain provides quick torque response, higher efficiency, weight reduction, and increased vehicle space.

In order to provide high torque density with excellent efficiency and overload capability, permanent magnet synchronous machines (PMSMs) with an outer-rotor have been proposed forin-wheel direct drive motors of EVs [4]. However, demagnetization and mechanical damage of rotor's magnet is among the serious problem especially when used in extreme driving conditions. On the other hand, switched reluctance motor (SRM) offers a simple and rugged rotor structure where no PM used as compared with PMSM. Therefore, SRM is more robust against mechanical and thermal impacts. Nevertheless, SRM produces large torque ripples which are not suitable for direct drive power train [5]. More recently, research and development on permanent magnet flux switching machine (PMFSM) is become more attractive due to several excellent features of physical compactness, robust rotor structure, higher torque and power density, and high efficiency. The rotor is salient and robust without winding or PM. As the magnets are located on the stator, the temperature rise of the magnets is easily managed [6]. Thus, the PMFSM can inherit selected advantages of both of the PMSM and SRM [7-10]. The PMFSM was first introduced as single-phase alternator in 1955 [7], while a three-phase machine was first reported in 1997 [11]. As such of advance machines, it was widely used in many applications such as in aircrafts, automotive traction drives, and wind power generations [10, 12, and 13]

Since, the outer-rotor configuration is more suitable for direct drive, the PMFSM with outer-rotor has been proposed only for light EV applications [14]. It provides essentially sinusoidal back-electromotive force (emf) and high torque at low speed. However, constant PM flux of PMFSM makes it difficult to control which requires field weakening flux at high speed conditions. In addition, with rapid increased in the price of rare-earth magnet, the cost of the motor is also become higher. Therefore, as one of the candidate that can overcome the problems, a new structure of outer-rotor hybrid excitation flux switching machine (ORHEFSM), consist of less rare-earth PM and field excitation coil (FEC) on the stator has been proposed by the authors as described in [15]. The proposed motor has simple in structure and expected can provides much higher torque and power density.

In this paper, the impact of rotor pole number on the characteristics of ORHEFSM is presented. Various rotor pole numbers for the proposed motor with 12 stator slots have been investigated in order to determine the optimal performances. The effect of rotor pole number on the electromagnetic performance such as flux linkage, cogging torque and torque ripple, back electromagnetic force (back-emf), output torque and power are analysed based on 2-D finite element analysis (FEA). The design restrictions and specifications of ORHEFSM are based on the interior permanent magnet synchronous machine (IPMSM) installed in Toyota Lexus RX400h as described in [16].

This paper is organized as follows. Section 2 discusses the rotor pole number determination and the operating principles of ORHEFSM. In Section 3, the design requirements, restrictions and specifications of the proposed motor is presented. The performances analysis of ORHEFSM based on 2-D FEA with the change of rotor pole numbers are explained in Section 4. Finally, conclusions are given in Section 5.

## 2. Operating Principles of ORHEFSM

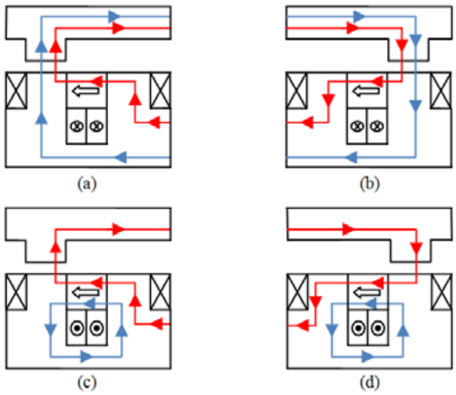


Fig. 1.Principle operation of ORHEFSM (a)$\theta_e$ = 0º (b) $\theta_e$ = 180º more excitation, (c) $\theta_e$ = 0º (b) $\theta_e$ = 180º less excitation

The concept of PMFSM was first introduced in the middle of 1950's [11], while for the HEFSM was introduced in year 2007 [9]. The term "flux switching" is introduced due to the changing of the polarity of the flux linkage by following the motion of salient pole rotor. The flux source of PMFSM is only come from the PM, whereas for the HEFSM is come from two sources which are PM and DC field winding. In both cases, all the active parts are located on the stator with the armature and PM (DC field winding) allocated to alternate stator teeth. The advantage of this machine is robust rotor structure that suitable for high speed applications. In addition, the FEC can be used to control the generated flux with variable capabilities. In the proposed ORHEFSM, the possible number of rotor pole and stator slot is defined by,

$$N_r = N_s\left(1 \pm \frac{k}{2q}\right) \tag{1}$$

where $N_r$ is the number of rotor poles, $N_s$ is the number of stator slots, $k$ is the natural number, and $q$ is the number of phases. For the proposed motor, $q$ = 3, $N_s$ =12 and $N_r$ is even numbers that varies from 10 to 26.

In this proposed motor, the motor rotation through $1/N_r$ of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is $N_r$ times of the mechanical rotational frequency. In general, the relation between the mechanical rotation frequency, $f_m$ and the electrical frequency, $f_e$ for the proposed machine can be expressed as,

$$f_e = N_r \bullet f_m \tag{2}$$

where$f_e$ is the electrical frequency, $f_m$ is the mechanical rotation frequency and $N_r$ is the number of rotor poles respectively.

The operating principle of the proposed ORHEFSM is illustrated in Fig. 1. The single piece of rotor is shown in the upper part that make the motor more robust which similar to SRM, and the stator is presented in the lower part, where the PM, FEC, and armature coil are located. The PM and FEC is put between two stator poles to generate excitation fluxes that creates the term of "hybrid excitation flux". In Fig. 1(a) and (b), its demonstrate that the flux generated by PM and FEC are flows from the stator into the rotor and from the rotor into the stator, respectively to produce a complete one flux cycle. The combine flux generated by PM and FEC established more excitation fluxes that capable to produce higher torque of the motor. When the rotor moves to the right, the rotor pole goes to the next stator tooth, hence switched the magnitude and polarities of the flux linkage. The flux does not rotate but shifts clockwise and counterclockwise direction with each armature current reversal. According to Fig. 1(c) and (d), only the PM flux flows from the stator into the rotor and from the rotor into the stator, respectively, while the FEC flux is only circulating on its particular winding. This condition established less excitation flux and generates less torque.

## 3. Design Methodology

In this paper, the design study is conducted based on 2D-FEA using JMAG-Designer ver. 12.0 released by Japan Research Institute (JRI). The initial structure and dimensions of the 12Slot-10Pole ORHEFSM are illustrated in Fig. 2 and Table 1, respectively. Furthermore, the design restrictions and specifications are similar as interior permanent magnet synchronous motor (IPMSM) installed in Toyota Lexus RX400h as depicted in Table 2. The proposed motor consists of 12 PMs and FECs winding which allocated uniformly in the midst of each armature coil slot around the stator. The three phase armature coils are accommodated in each ¼ of the stator body periodically resulting the machine having 24 stator teeth. As the rotor rotates, the fluxes generated from PMs and FECs are linked with the armature coils. The PM material used is NEOMAX 35AH whose residual flux density and coercive force at 20 ºC are 1.2 T and 932 kA/m, respectively. The electromagnetic steel, 35H210 is used for the rotor and the stator core.

In this study, the performances of the proposed motor are investigated for various rotor pole numbers range from 10Pole to 26Pole with retains the stator slot number at 12Slot. Design parameters of the machine are shown in Fig. 3. Firstly, the area of armature coil slot and FEC slot are calculated from Eq. (3) and Eq. (4) to give the optimum number of turns. In this work, the motor parameters are divided into two groups, namely, those related to stator iron core and rotor iron core. On the stator iron core, it is subdivided into three components which are the PM shape, FEC slot shape, and armature slot shape. The rotor parameters involved are the inner rotor radius (D1), rotor pole depth (D2), and rotor pole arc width (D3). The distance between airgap and PM is (D4). The PM slot shape parameters are the PM depth (D5), and the PM width (D6), while for the FEC slot parameters are FEC slot depth and FEC slot width, (D7) and (D8) respectively. Finally, the armature coil parameters are armature coil slot depth (D9) and the armature coil slot width (D10). Based on the identified motor parameters, the deterministic design optimization method is used to obtain the optimal performances of the proposed motor. In summary, the motor parameters D1 to D10 are changed repeatedly from (D1) to (D10) until the target performances of torque and power are achieved.During the design process, the air gap length is kept as constant with 0.8mm.

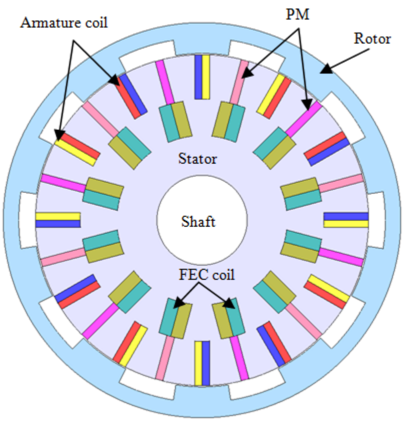


Fig. 2. Initial design structure of ORHEFSM

Table 1. Initial dimension of ORHEFSM

| Descriptions | ORHEFSM |
|---|---|
| Number of phase | 3 |
| Number of stator pole | 12 |
| Motor radius (mm) | 132 |
| Motor stack length (mm) | 70 |
| Shaft radius (mm) | 30 |
| PM area ($mm^2$) | 70 |
| Field excitation coil area ($mm^2$) | |
| Armature coil area ($mm^2$) | 140 |
| Air gap (mm) | 0.8 |
| Number of phase turns | 7 |
| Number of DC winding turns | 44 |

Table 2. ORHEFSM Design Restrictions and Specifications

| Descriptions | IPMSM | ORHEFSM |
|---|---|---|
| Max. DC-bus voltage inverter (V) | 650 | 650 |
| Max. inverter current ($A_{rms}$) | 360 | 360 |
| Max. current density in armature coil, $J_a$ ($A_{rms}/mm^2$) | 30 | 30 |
| Max. current density in FEC, $J_e$ ($A/mm^2$) | 30 | 30 |
| PM weight (kg) | 1.1 | 1.0 |
| Maximum torque (Nm) | 333 | >333 |
| Maximum power (kW) | 123 | >123 |

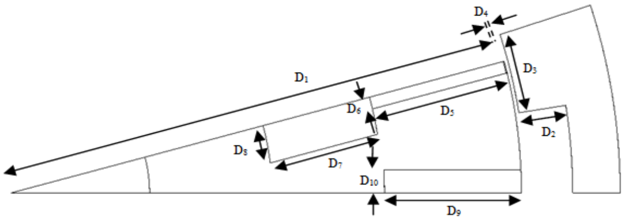


Fig. 3. Design parameters of ORHEFSM

$$S_a = \frac{I_a N_a}{\alpha J_a} \quad (3)$$

$$S_e = \frac{I_e N_e}{\alpha J_e} \quad (4)$$

## 4. FEA Based Performance Analysis of Initial Design ORHEFSM

In the case of inner-rotor flux switching machines (FSMs) that have been studied, the rotor pole number $N_r$ is normally designed as close to stator slot number $N_s$ to maximize the performances of the machine [14 and 17].

Since, there is very little study has been carried out for outer-rotor FSM, an appropriate number of pole for the machines must be determined to find the optimal performances. As reported in [14, 18, and 19], the analysis have done for $N_r$ ranges from 14 to 26 and $N_s$ is fixed at 12. All of them concluded their analysis by choosing 12S-22P as the most suitable for the proposed three-phase outer rotor PMFSM. From the studied, it is shown that $N_r$ = 22 exhibits the highest back-emf and rated torque with considerably low cogging torque.

Therefore, with hard to find any research on ORHEFSM, this research concerns on investigation of ORHEFSM used for in-wheel drive EV applications. The main objective of this work is to examine the appropriate rotor pole number that can give optimal torque and power on the initial design motor. Hence, in this study the analysis on the rotor pole number, $N_r$ is ranging from 10 to 26 with the fixed of stator slot, $N_s$ at 12.

### 4.1. Armature Coil Arrangement Test

Initially, the operating principle of ORHEFSM for each combination of rotor pole number is necessarily to be validated in order to examine the position of armature coil phase. For each combination of stator slot-rotor pole numbers, coil arrangement test are determined individually in all 12 armature coils. In order to implement this, all sources of DC FEC and armature coils supply is set to 0 A in which the flux source is only come from PM. By initially set all the DC FEC and armature winding in counter-clockwise direction, the flux linkages generated by PM is observed on each armature coil winding. Then, the resulting flux linkages are evaluated and compared to identify the three phase armature coil of the motor in which separated by 120º phase shifted between all phases. Moreover, the flux linkages with the same phase is put together and defined as U, V, and W phase. The same procedures are applied for all stator slot-rotor pole combinations to confirm the principles and three phase flux linkages of ORHEFSM.

### 4.2. Magnetic Flux Characteristic

The amplitude of the magnetic flux linkage of ORHEFSM with 12 stator slot at various rotor pole numbers is investigated. The magnetic flux generated by PM only and DC FEC only is demonstrated in Fig. 4 and Fig. 5, respectively. From both figures, it is clearly show that the highest amplitude of the magnetic flux is achieved for the combination of 12S-10P configuration. This means that the 12S-10P configuration has possibility to provide higher torque and power of ORHEFSM. For the rest of rotor pole numbers, the amplitude of the magnetic flux is much less compared with 12S-10P configuration. It is expected that this scenario is due to some flux leakage occurs when higher rotor pole number used in the design and will further investigated in the future.

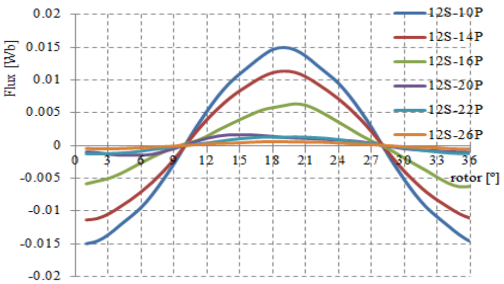


Fig. 4. Magnetic flux linkage of PM only

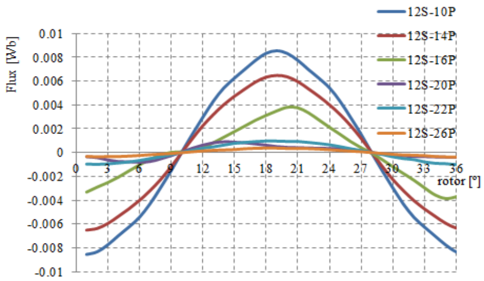


Fig. 5.Magnetic flux linkage of FEC only

### 4.3. Induced Voltage at Open Circuit Condition

The induced voltage generated from PM with the speed of 3000 r/min at open circuit condition for various rotor pole numbers are illustrated in Fig. 6. From the figure, the motor with 12S-10P configuration has highest amplitude with approximately 82.4 V. When the rotor pole number is increased, the magnitude of the induced voltage are reduces and the motor design with 12S-26P has the lowest amplitude with approximately only 6.3 V. In summary, the higher the $N_r$, less generated induced voltage and the signal is more sinusoidal. In all configuration of rotor pole numbers, the waveform of the induced voltage are looks distorted and this is due to the third harmonic order from the initial flux.

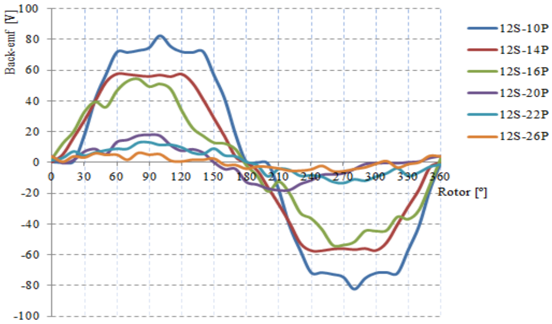


Fig. 6. Induced voltage at 3000 r/min

*4.4. Cogging Torque Characteristic*

The cogging torque characteristic for various rotor pole numbers is illustrated in Fig. 7. It is clearly shown that 12S-16P configuration has highest peak to peak cogging torque followed by 12S-20P with 44.4 Nm and 20.0 Nm, respectively. While for the rest of rotor pole number, the peak to peak cogging torque is less than 10 Nm. Therefore, by further design refinement and optimization, it is expected that the cogging torque of the proposed motor can be reduced into an acceptable condition.

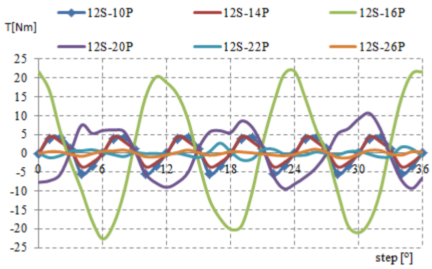


Fig. 7. Cogging torque

*4.5. Load Analysis*

Finally, by set the armature current density at maximum condition, the output torque and power at various FEC current densities is demonstrated in Fig. 8 and Fig. 9, respectively. It is shown that the maximum torque is appears at 12S-14P configuration while the maximum power is occurs at 12S-10P configuration with approximately 250 Nm and 104 kW, respectively. For 12S-20P and 12S-22P, the output torque and power start to reduce when $J_e$ is employed. This is due to, a lot of magnetic fluxes are cancel with the flux from armature coil and produces negative torque. Further investigation on these rotor pole configurations is necessary to identify the problem.

## 5. Conclusion

In this paper, the impact of rotor pole number on the characteristic of ORHEFSM has been presented. Based on 2-D FEA and by taking several factors on motor design, the motor with 12S-10P shows a good possibility to achieve the target performances and is selected to be further improved in future. Therefore, by further design refinement and optimization on the selected stator slot and rotor pole configuration, the target performances of ORHEFSM are expected can be achieved.

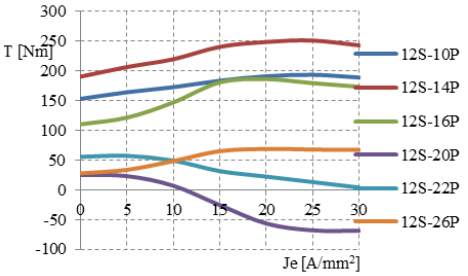


Fig. 8. Torque vs$J_e$ at maximum $J_a$

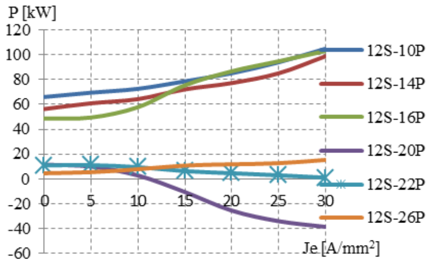


Fig. 9. Power vs$J_e$ at maximum $J_a$

## References


[1] J. King, The King Review of low-carbon cars of low-carbon cars - Part II: recommendations for action, March 2008. Available at: www.hm-treasury.gov.uk/king

[2] IEA-HEV Outlook, International Energy Agency Implementing Agreement on Hybrid and Electric Vehicles, “Outlook for hybrid and electric vehicles,” 2008 [Online] Available: http://www.ieahev.org/pdfs/iahev_ outlook_2008.pdf

[3] W. Xu, J. Zhu, Y. Guo, S. Wang, Y. Wang, and Z. Shi, “Survey on electrical machines in electrical vehicles,” 2009 International Conference on Applied Superconductivity and Electromagnetic Devices, no. c, pp. 167–170, Sep. 2009.

[4] W. Fei, P. Luk, and K. Jinupun, “A New Axial flux magnet segmented- armature-torus machine for in-wheel direct drive applications,” IEEE Power Electronics Specialist Conference, pp. 2197-2202, 2008.

[5] W. Fei, P. Chi, K. Luk and J. S. Y. Wang, “A Novel Outer-Rotor Permanent-Magnet Flux-Switching Machine for Urban Electric Vehicle Propulsion,” in 3rd International Conference on Power Electronics Systems and Applications (PESA), pp. 1–6, 2009.

[6] Z.Q. Zhu, and J.T Chen, "Advanced flux-switching permanent magnet brushless machine," IEEE Trans. Magn., vol 46, no. 6, pp. 1447-1452, Jun 2010

[7] S. E. Rauch and L. J. Johnson, “Design principles of flux switch altenators,” AIEE Trans., vol 74III, no. 12, pp. 1261-1269, 1955.

[8] Y. Chen, S. Chen, Z.Q. Zhu, D. Howe, and Y.Y. Ye, “Starting torque of single phase flux switching permanent magnet motors,” IEEE Trans. Magn., vol 42, no. 10, pp. 3416-3418, 2006.

[9] E. Hoang, M. Lecrivain, and M. Gabsi, “A New Structure of a Switching Flux Synchronous Polyphased Machine,” in European Conference on Power Electronics and Applications, no. 33, pp. 1–8, 2007.

[10] Y. Amara, E. Hoang, M. Gabsi, and M. Lecrivain, “Design and comparison of different flux-switching synchronous machines for an aircraft oil breather application,” Euro. Trans Electr. Power, no. 15, pp. 497-511,2005.

[11] E. Hoang, A. H. Ben-Ahmed, and J. Lucidarme, "Switching Flux PM Polyphased synchronous machine," in Proc. 7$^{th}$Eur Conf. Power Electronics Appl., Sept 1997, pp. 903-908.

[12] C. Pollock, H. Pollock, R. Borron, J. R. Coles, D. Moule, A. Court, and R. Sutton, "Flux-switching motors for automotive applications," IEEE Trans. Ind. Appl., vol. 42, no. 5, pp. 1177-1184, Sept/Oct 2006.

[13] M. J. Jin et al, "Cogging torque suppression in a permanent magnet flux-switching integrated -starter generator," IET Electric Power Appl., vol 4, no. 8, pp. 647-656, Aug 2010.

[14] W. Fei, P. Chi, K. Luk, S. Member, J. X. Shen, Y. Wang, and M. Jin, “A Novel Permanent-Magnet Flux Switching Machine With an Outer-Rotor Configuration for In-Wheel Light Traction Applications,” IEEE Transactions on Industry Applications, vol. 48, no. 5, pp. 1496–1506, 2012

[15] 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", IEEE Int. Power and Energy Conference (PECON2012), pp. 928-933, Dec 2012.

[16] E. Sulaiman, T. Kosaka, N. Matsui, and M. Z. Ahmad, “Design Studies on High Torque and High Power Density Hybrid Excitation Flux Switching Synchronous Motor for HEV Applications,” in IEEE International Power Engineering and Optimization Conference (PEOCO), 2012, pp. 333–338,June 2012.

[17] J.T. Chen, and Z. Q. Zhu, "Influence of rotor pole number on optimal parameters in flux-switching PM brushless AC machines by the lumped parameter magnetic circuit model," IEEE Trans. Ind. Appl. , vol. 46, no. 4, pp. 1381-1388, Jul/Aug 2010.

[18] W. Fei, P.C.K. Luk, J. Shen, and Y. Wang, "A novel outer-rotor permanent magnet flux switching machine for urban electric vehicle propulsion," Proc. on Int. Conference Power Electronics Systems and Application, 2009.

[19] Y. Wang, M.J. jin, J. Shen et al, "An outer-rotor flux switching permanent magnet machine for traction applications," IEEE Energy Conversion Congress and Exposition, pp. 1723-1730, 2010.