Preliminary Design of Field Excitation Flux Switching Motor on the Impact of Various Rotor Pole Number for Hybrid Electric Vehicles

Zhafir Aizat Husin, Erwan Sulaiman, Faisal Khan and Mohd Fairoz Omar
Department of Electrical Power Engineering
Universiti Tun Hussein Onn Malaysia, Locked Bag 101
Batu Pahat, Johor, 86400 Malaysia
zhafiraizat69@gmail.com and erwan@uthm.edu.my

***Abstract*—This paper presents a new structure of field excitation flux switching motor (FEFSM) as an alternative candidate of non-permanent magnet (PM) machine for hybrid electric vehicles (HEVs) drives. The effect and performances of rotor pole number with similar armature coil slot configurations on the stator of the proposed FEFSM is analyzed for HEV applications. The stator of projected machine consists of iron core made of electromagnetic steels, armature coils and field excitation coils as the only field mmf source. The rotor is consisted of only stack of iron and hence, it is reliable and appropriate for high speed operation. Under some design restrictions and specifications, design principles and initial performances of the proposed motor at various rotor pole numbers with 8 stator slots are demonstrated. Initially, the coil arrangement tests are examined to validate the operating principle of the motor and to identify the zero rotor position. Furthermore, the profile of flux linkage, induced voltage, cogging torque and torque characteristics are observed based on 2D finite element analysis (FEA). The results obtained show that the appropriate combination of stator slot-rotor pole configurations are 8S-12P and 8S-4P with lowest cogging torque as well as sinusoidal flux waveforms and 8S-8P with highest average torque and power, respectively. Thus, by further design modification and optimization, it is expected that the motor will successfully achieved the target performances for HEV application.**

***Keywords*—*Field Excitation Flux Switching Motor, Hybrid Electric Vehicle and Field Excitation Coil (DC FEC*)**

I. INTRODUCTION

In the mid 1950s, the initial concept of flux switching motor (FSM) has been published. In general, permanent magnet flux switching motor (PMFSM), field excitation flux switching motor (FEFSM), and hybrid excitation flux switching motor (HEFSM) are three types of FSM as illustrate in Fig. 1. Both FEFSM and PMFSM has only permanent magnet and field excitation coil (FEC), correspondingly as the main source of flux, whilst HEFSM combines both FEC and permanent magnet as their main flux sources.

Permanent magnet (PM) machines have some drawbacks because of the rare earth magnet material is expensive and the working environmental temperature may limit its application. In fact, the flux-weakening operation at high speed is relatively difficult for PM machines due to fixed PM excitation.

In the advanced research, the only machine that already installed for HEVs is interior permanent magnet synchronous motor (IPMSM) as depicted in Fig. 2 where it has developed to enhance power density of the machine [1]. Despite of fine operated and superior performances, this machine do not miss approached by deficiency for instance IPMSM now have complex form and configuration that give difficulty to undertake the process of optimizing the design of this motor. Moreover, the use of PM will result in a constant state of flux and cannot be controlled as well a burden because of expensive rare earth magnet prices and also high copper loss due to distributed armature windings.

Thus, FEFSM with a new form has been created as a new candidate that can address these problems in which the uses of permanent magnet is totally excluded while the FEC is located on the stator [2]-[4]. The proposed motor has a simple and easy structure and it is expected to provide much higher power density and torque [5]-[7]. The impact of rotor pole number of the proposed motor with 8 stator slots is analyzed in this paper in effort to establish the optimal performances. The impact of rotor pole number on the electromagnetic performances such as induced voltage, cogging torque, flux linkage, output power and torque are analyzed based on 2-D finite element analysis (FEA). In the proposed FEFSM, the probable number of rotor pole and stator slot is defined as in (1),

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

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 = 1, N_s =8 and N_r is even numbers that varies from 4, 8 and 12. The motor is operated based on the principle of switching flux and to describe machines in which the stator tooth flux switches polarity following the motion of a salient pole rotor [8]. The principle operation of FEFSM is demonstrated in Fig. 3. Fig. 3 (a) and (b) show the movement of the FEC flux into the rotor while (c) and (d) visualize the movement of FEC flux into the stator which creates one complete cycle movement of fluxes. The stator fluxes switches between the alternate stator teeth because of the each reversal of armature current shown by the transition involving Fig. 3 (a) and (b) [9].

II. Design Restrictions, Specifications and Parameters of FEFSM

The motor parameters, restrictions and target specifications of the projected FEFSM for HEV applications are scheduled in Table I. The inverter is set at the maximum of 375V DC bus voltage as well as inverter current at 360V. Assuming water jacket system is in use as the cooling system for the machine the limit of the current density is set to the maximum 30Arms/mm^2 for armature winding and 30A/mm^2 for FEC, respectively. The motor stack length, the outer diameter, the air gap and the shaft radius of the major parts of the machine design being 70mm, 264mm, 0.8mm and 30mm, respectively, alike with existing IPMSMs. The electrical steel 35H210 is used for stator and rotor body.

The numbers of turns of FEC and armature coil are defined from (2) and (3), respectively. The motor's filling factor is put at 0.5, whilst the slot area of armature slot and FEC slot is calculated, correspondingly. To ensure flux moves from stator to rotor equally without any flux leakage, the design of the proposed machine is defined as in (4). The rotor is consisted of only stacked soft iron sheets and can be expected to rotate at high-speed because the rotor structure is mechanically robust. Furthermore, the maximum expected torque of 70Nm and power is set to be higher than 41kW, respectively. The commercial finite element analysis (FEA) package, JMAG-Designer ver.13.1, released by Japan Research Institute is used as 2D-FEA solver in this design.

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{2}$$

$$N_e = \frac{J_e \alpha S_e}{I_e} \tag{3}$$

$$S_W = R_W \tag{4}$$

Where *N, J, α, S* and *I* are number of turns, current density, filling factor, slot area and input current, respectively. For the subscript *a* and *e* represent armature coil and FEC, respectively. The machine configurations and windings of 8 stator slots with 4, 8 and 12 pole numbers are illustrated as in Fig. 4 and Fig. 5, respectively. The FEC directions for all rotor pole numbers are in alternate direction, counter-clockwise polarity and clockwise polarity.

Primarily, the selection of the proposed FEFSM is designed with the following assumptions; (i) The inner radius is set to 30 mm for the motor's shaft while rotor radius is 97.2 mm which is 73% of 132 mm motor radius and within the range of general machine split ratio, (ii) The stator outer core thickness is set to be half of the stator inner length with the assumptions that the fluxes are divided into two parts, (iii) The depth of the rotor pole is set to be 1/3 of rotor radius to give much depth for the flux to flow, (iv) The FEC and armature coil slot opening angle are set to 5.625°, which is half of the stator slot opening angle

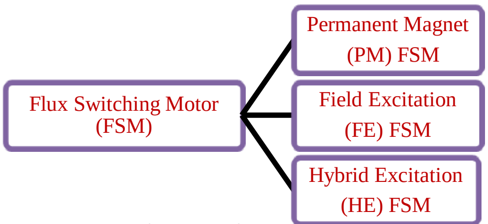


Fig. 1. Classifications of Flux Switching Machine

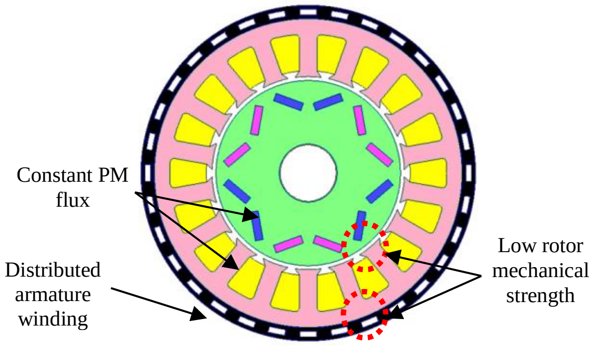


Fig. 2. Cross sections of IPMSM

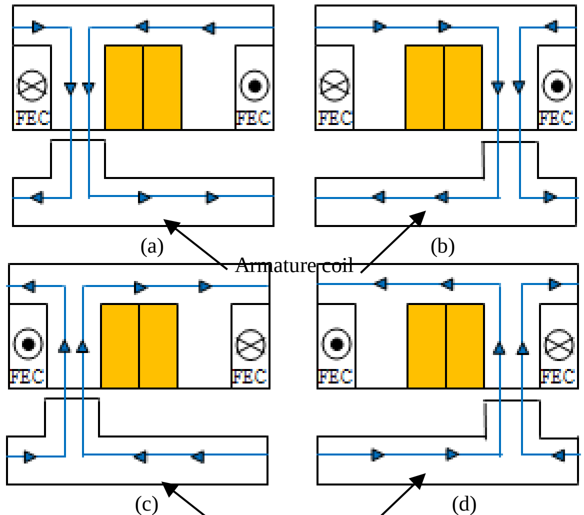
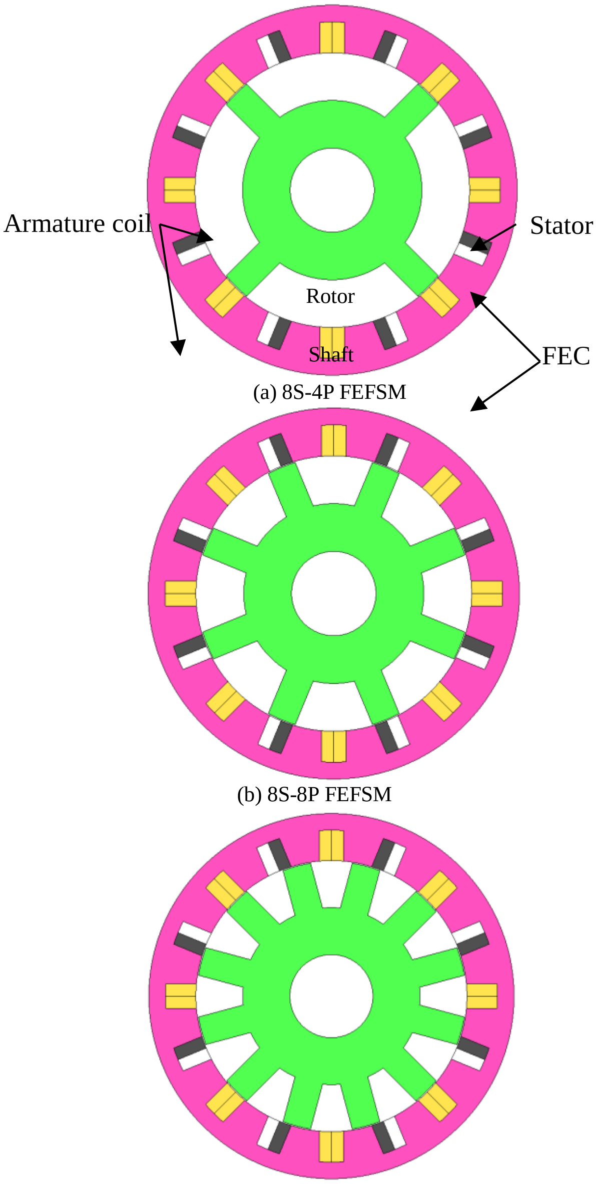


Fig. 3. Operating principle of FEFSM (a) θ*e*=0° and (b) θ*e*=180° fluxes move from stator to rotor (c) θ*e*=0° and (d) θ*e*=180° fluxes move from rotor to stator

TABLE I. FEFSM Propose Specifications and Limitations

Items	IPMSM	FEFSM
Max. inverter DC-bus voltage (V)	650	375
Max. current of inverter (A_{rms})	Confidential	360
Armature winding J_a, maximum current density (A_{rms}/mm^2)	Confidential	30
Excitation winding J_e, maximum current density (A/mm^2)	NA	30
Stack length of motor (mm)	70	70
Outer diameter of stator (mm)	264	264
Length of air gap (mm)	0.8	0.8
Radius of shaft (mm)	30	30
Weight of PM (kg)	1.1 (est.)	0
Maximum torque (Nm)	333	> 70
Maximum power (kW)	123	> 41
Power density (kW/kg)	3.5	> 1.17



(a) 8S-4P FEFSM

(b) 8S-8P FEFSM

(c) 8S-12P FEFSM

Fig. 4. Preliminary design of the FEFSM configuration

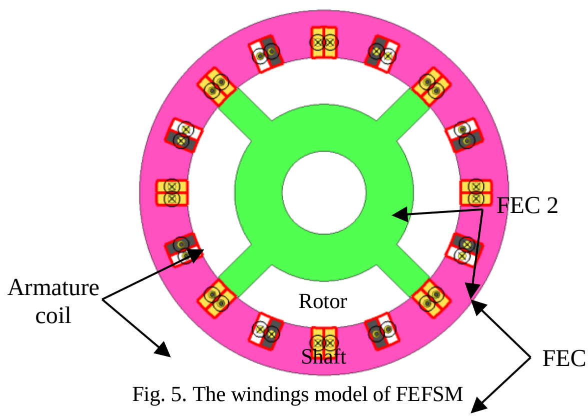


Fig. 5. The windings model of FEFSM

of 11.25°. (v) The total coil slot area of both FEC and armature coil is less than the stator teeth area. Therefore, it is expected that all fluxes from both coils to have sufficient space to flow in the stator yoke, without magnetic saturation.

III. DESIGN PERFORMANCE AND RESULTS BASED ON 2D FINITE ELEMENT ANALYSIS

To ensure the performances of the machine is at maximum, the rotor pole number N_r is normally designed as close to stator slot number N_s based on case of inner-rotor flux switching machines (FSMs) that have been studied [10]. An appropriate number of pole for the motors must be determined to find the optimal performances since there is very little study has been carried out. As studied in [11, 12, and 13], it have been analyzed for N_r varies starting 14 until 26 and N_s is constant at 12. Entire of them concluded their investigation by choosing 12S-22P as the most appropriate for the proposed three-phase outer rotor PMFSMs because N_r equal 22 exhibits the lowest cogging torque and highest back-emf. Nevertheless, the study presented is only focus on the principle of cogging torque and induced voltage characteristic.

In order to find the optimal performances and suitable to be further optimized, other parameters such as generated magnetic flux, output power and torque also may need to inspect. As the proposed motor to be applied for HEV applications, the high power density and torque capability is one of predominantly significance constraint besides of cogging torque and back-emf. This is due to the existence of the adverse effects. 2-D FEA investigation is implemented in this study to examined the effects of various rotor pole numbers on the characteristic of FEFSM also N_r range is set from 4, 8 and 12 while N_s is fixed at 8.

A. Coil Arrangement Test

Coil arrangements are examined in each armature coil slots singly in order to verify the principle operation of the FEFSM and to set the arrangement of each armature coil phase, where all armature coils are wounded in counter-clockwise direction while FEC are wounded in clockwise and counter-clockwise direction. The flux linkages at each coil are observed and the armature coil phases are defined according to the conservative single-phase as demonstrated in Fig. 6. The armature coil flux can start the rotor at the maximum as the U flux satisfies the zero rotor position indicated by red dotted line.

B. FEC Flux Linkage at various FEC current density, J_E

Fig. 7 demonstrates the profile of flux linkages of U Flux for the proposed motor at a range of rotor pole numbers. It is visibly shows that the flux linkage of 12S-10P FEFSM has the uppermost amplitude compared with the rest of rotor pole numbers configuration. The reason behind this is that the flux is easily flow from the stator to the rotor. The amplitude of flux linkage is reduced as the rotor pole number increased.

C. Induced Voltage at Open Circuit Condition

The fundamental of induced voltage or back-emf generated from conventional 3-phase fluxes for various rotor pole numbers is illustrated in Fig. 8. As seen from the graph, 12S-

14P has the higher induced voltage follow by 12S-10P. From 12S-16P to 12S-22P as the higher the N_r, less generated induced voltage. From the studied, the projected machine with highest back-emf is selected.

D. Cogging Torque

The torque ripple feature for a range of rotor pole numbers is shown in Fig. 9. From the graph, is evidence that 8S-8P configuration has highest peak to peak torque ripple chased by 8S-4P with 530Nm and 100Nm, correspondingly. This is due to the effect of high FEC flux linkage flow to the rotor. While for 12 rotor pole numbers, the peak to peak torque ripple is 0.14Nm. High torque ripple will give high noise and vibration that is unnecessary for the performance of the motor.

E. Torque and Power Characteristics at various J_E

At last, by situate the armature coil current density, J_A at maximum conditions, the torque profile and power at a various FEC current densities, J_E is validated in Fig. 10 and Fig. 11, correspondingly. From the figure, it is revealed that the highest torque and power appear at 8S-8P about 236.6Nm and 28.6kW, respectively. For 8S-12P, the torque profile and power produce is small. It is necessary to do further investigation to identify the problem on these rotor pole configurations.

The maximum torque and power obtained is still distant from the target requirements. In order to suit the goal, the deterministic optimization method [14]-[15] will be conducted in the future as the design parameters are separated into three portions. Portion 1 related with rotor core shape while portion 2 is FEC slot shape and portion 3 is armature coil slot shape since the designs technique clarify above are treated repetitively by varying D1 to D7 parameters in Fig. 11 until the intention power and torque are attained.

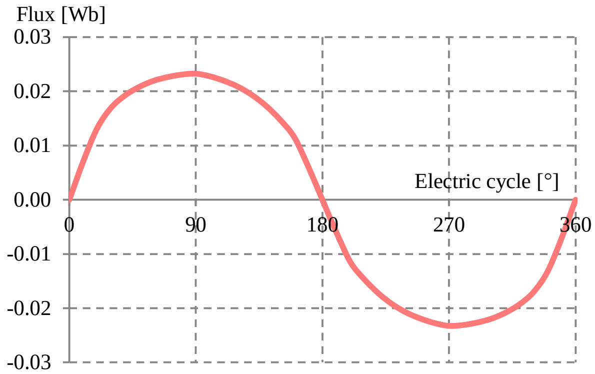


Fig. 5. Conventional single-phase flux

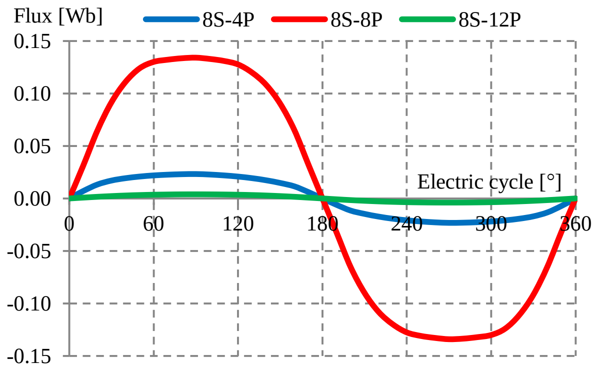


Fig. 6. Flux Linkage at various rotor pole numbers

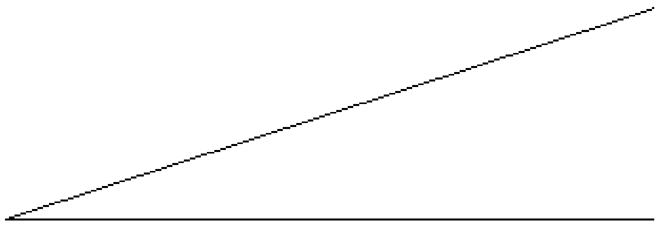


Fig. 11. Design pa

IV. Conclusion

In this paper, design studies and performance analysis of various slot-poles of FEFSM for traction drive in HEV applications have been presented. The profile of flux linkage, induced voltage, cogging torque, torque characteristics and power are observed based on 2D- finite element analysis (FEA). The appropriate combinations of stator slot-rotor pole configurations are 8S-12P and 8S-4P with lowest cogging torque as well as sinusoidal flux waveforms and 8S-8P with highest average torque and power, respectively. There is no usage of permanent magnet and thus, it can be expected as very low cost machine. The shape of the proposed motor is very simple which expose better way of design optimization. Thus, by further design modification and optimization it is expected that the motor will successfully achieved the target performances.

Acknowledgment

This research was supported by ERGS (Vot E030) under Research, Innovation, Commercialization and Consultancy Management (ORICC) UTHM, Batu Pahat and Ministry of Higher Education Malaysia (MOHE).

References

[1] M.A. Rahman: “IPM Motor Drives For Hybrid Electric Vehicles”, InternationalAegean Conference on Electrical Machines and Power Electronics, Sept. 2007.

[2] E. Sulaiman, T. Kosaka, and N. Matsui, “A New Structure of 12Slot-10Pole Field-Excitation Flux Switching Synchronous Machine for Hybrid Electric Vehicles”, Proc. of 14th European Conference on Power Electronics and Applications, Birmingham, Sept. 2011.

[3] E. Sulaiman, T. Kosaka, and N. Matsui, “Design Study and Experimental Analysis of Wound Field Flux Switching Motor for HEV Applications”, XXth IEEE Int. Conf. on Electrical Machines (ICEM 2012), Marseille, France, Sept 2012.

[4] E. Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad and T. Kosaka, “Performances Comparison of 24s-10p and 24s-14p Field Excitation Flux Switching Machine (FEFSM) With Single DC-Coil Polarity”, International Journal of Energy & Power Engineering Research, Vol, 1, pp. 24-31, Dec 2013.

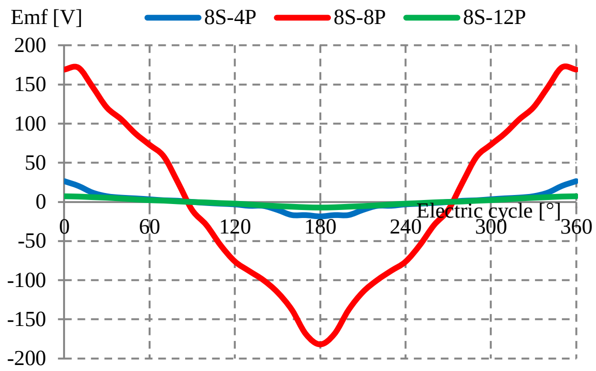


Fig. 7. Induced Voltage at various rotor pole numbers

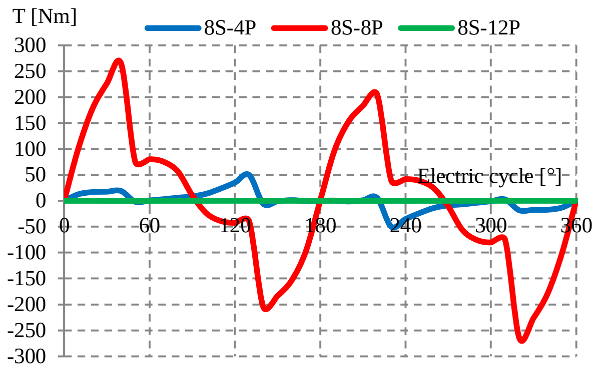


Fig. 8. Cogging Torque

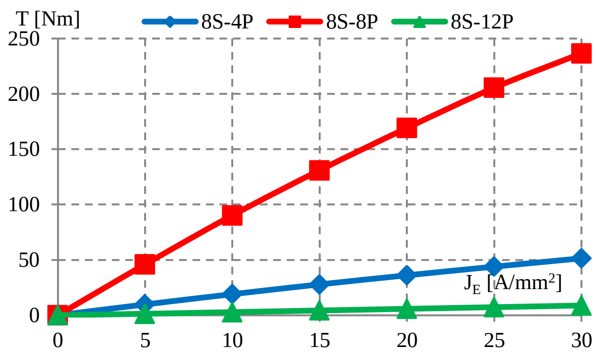


Fig. 9. Torque vs J_E at maximum J_A

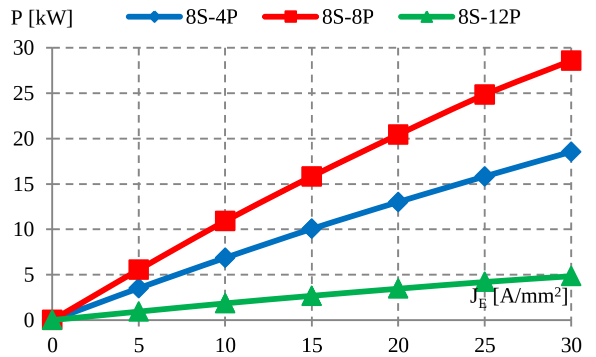


Fig. 10. Power vs J_E at maximum J_A

[5] E. Sulaiman, T. Kosaka, and N. Matsui, "Design and Analysis of High-Power/ High-Torque Density Dual Excitation Switched-Flux Machine for Traction Drive in HEVs", Renewable & Sustainable Energy Review, submitted for 3rd review, Jan 2014.

[6] 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.

[7] E. Sulaiman, T. Kosaka, and N. Matsui: "High power density design of 6slot-8pole hybrid excitation flux switching machine for hybrid electric vehicles", *IEEE Trans. on Magn.*, vol.47, no.10 pp. 4453-4456, Oct. 2011.

[8] S. E. Rauch and L.J. Johnson, 'Design principles of flux-switch alternators', Tans. AIEE, vol. 74 pt. III, pp. 1261-1268, 1955.

[9] E. Sulaiman, "Less Rare-Earth and High Power Density Flux Switching Motor for HEV Drives,‖ International Conference on Electrical machine ICEM pp. 15-23, June 2012.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] E. Sulaiman, T. Kosaka, and N. Matsui, "Design optimization and performance of a novel 6-Slot 5-Pole PMFSM with hybrid excitation for Hybrid Electric Vehicle", *IEEJ Trans. on Industry Appl., vol. 132, No. 2, Sec. D*, pp. 211-218, 2012.

[15] E. Sulaiman, T. Kosaka, and N. Matsui, "FEA-based Design and Parameter Optimization Study of 6-slot 5-pole PMFSM with Field Excitation for Hybrid Electric Vehicle," IEEE International Conference on Power and Energy (PECon 2010) pp. 206-201, Dec 2010.