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AT-14

Influence of Magnetic Saturation and Rotor Eccentricity on Back-EMF of Novel Hybrid-excited Stator Slot Opening Permanent Magnet Machine

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Abstract **– This paper introduces a novel hybrid-excited stator slot opening permanent magnet (PM) machine (HSSPMM). The operation principle of the machine is described and the effects of rotor eccentricity and magnetic saturation due to PMs on electromagnetic performance, with particular emphasis on back-EMF, are analysed by finite element method (FEM). It shows that different from the conventional PM machines, the open-circuit back-EMF in this novel HSSPMM should be zero but may become non-zero if significant magnetic saturation exists, and further, the rotor eccentricity has a detrimental effect on the waveforms, amplitudes and symmetries of 3-phases back-EMFs, as confirmed by FEM and tests.**

Index terms **– hybrid-excited machine, magnetic saturation, rotor eccentricity, stator slot opening PM machine**

I. INTRODUCTION

Hybrid-excited machines utilize both permanent magnets (PM) and DC-field windings for excitation and offer synergies of both PM-excited and DC-excited machines [1-3]. Different from the PM-excited machines, the hybrid-excited machines can use DC current to control flux in the air-gap with relatively low armature reaction control and exhibit improved flux-weakening performance, which is similar to wound field synchronous machines. However, the maximum efficiency and torque density of wound field synchronous machines are lower than the PM-excited machines due to additional excitation copper loss and the absence of PM, respectively. The hybrid-excitation machines have a good balance between the pros and cons of the PM-excited and wound field synchronous machines. In general, because of the synergies of PM and DC field excitations, the hybrid-excited machines have higher torque density than the wound field synchronous machines and also provide enhanced flux regulation capability, resulting in better efficiency and speed regulation.

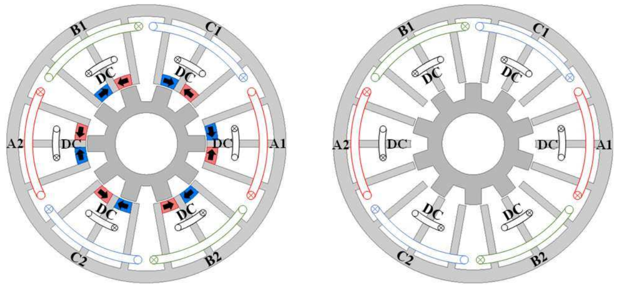
The idea of locating PMs in the stator slot opening area comes from [4, 5] which places PMs between adjacent stator teeth of switched reluctance machine to enhance the torque. The conventional hybrid-excited stator slot opening PM machine (HSSPMM) can then be modified by adding PMs between adjacent stator teeth in variable flux reluctance machine (VFRM) [6, 7]. The PMs are used to reduce the magnetic saturation produced by current excitation and enhance the torque density. Moreover, the HSSPMM maintains good flux regulation capability as the VFRM due to the DC excitation.

In this paper, a novel HSSPMM is developed by placing PMs in the slot opening area of the stator slots for field windings in a DC-excited switched flux machine (DC-SFM) [8]. The stator DC-SFM can be easily magnetically saturated due to both armature and DC excitations. However, the magnetic saturation can be reduced since the PM flux direction is opposite to that produced by current excitation, and meanwhile, the torque of the HSSPMM can be increased. Some similar hybrid-excited machines as the novel HSSPMM are available since the machine with wound field coil slots on the stator back-irons [9-12]. This type of machines can also be counted as putting PM and wound field coil in one slot especially when adjusting the field and armature winding slots, the slot area, and the PM shape as well, as shown in [13].

This paper aims to study how the open-circuit back-EMF of the novel HSSPMM will be affected by magnetic saturation and rotor eccentricity, together with other electromagnetic performance. The operation principle of the HSSPMM is firstly presented in detail in section II. The influence of magnetic saturation is introduced in section III. Furthermore, the influence of rotor eccentricity of the machine is given in section IV. The machine is also prototyped and tested at open-circuit and the amplitudes and waveforms of back-EMF will be validated under the influence of magnetic saturation and rotor eccentricity, which are also given in section IV.

II. MACHINE TOPOLOGY AND OPERATION PRINCIPLE

The novel HSSPMM has a coil span of one slot pitch for field windings (F1) while a coil spans over three slot pitches for armature windings (A3), as shown in Fig. 1(a), which can be modified from a DC-SFM by adding PMs in the stator slot opening area for field windings, as shown in Fig. 1(b). The adjacent PMs in the F1A3 HSSPMM have opposite magnetization direction. The armature windings are excited by sinusoidal AC currents fed from a standard 3-phase inverter. Additional benefit by putting PMs at the slot openings is to reduce the stator saturation caused by current excitation on load condition, Fig. 2(a) and (b), since the PM flux has opposite direction of the flux produced by current excitation. This will lead to an enhancement of the electromagnetic torque as shown in Fig. 2 (c). The detailed electromagnetic torque performance of two types of machines are listed in Table I.



(a) F1A3 HSSPMM (b) DC-SFM [7]

Fig. 1. HSSPMM and DC-SFM with F1A3 coil windings.

The operation principle of the F1A3 HSSPMM is similar to that of the conventional HSSPMM. Without the consideration of magnetic saturation, the PM flux will be shunted in the stator when the machine has no current excitation which is shown in Fig. 3(a). When positive excitation current is applied, the flux path is shown in Fig. 3(b). Since the flux produced by current

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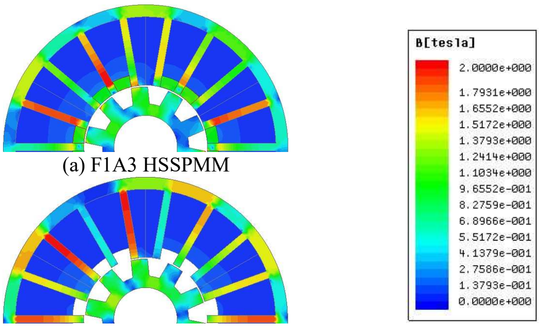
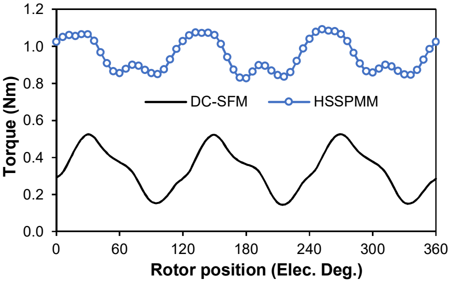
excitation, which is shown in red, has opposite direction to the PM flux, the shunted PM flux can be pushed to the rotor via air-gap which is followed by the black line. When the field current is low, the machine will be mainly dominated by PM source with the total flux path similar to the PM flux path. With the increasing of field coil current, the field strengthening control may become dominant gradually.



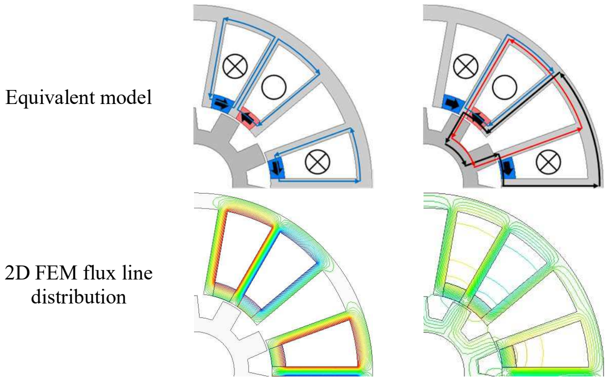
(a) F1A3 HSSPMM

(b) DC-SFM



(c) Electromagnetic torque waveforms

Fig. 2. Electromagnetic torque and flux density distributions for DC-excited machines with/without PMs at rated currents (I_{peak} = 6.55A, I_{dc} = 4.73A).



(a) I_{dc} = 0A (b) I_{dc} > 0A

Fig. 3. DC and flux paths in quarter machine models with linear stator and rotor material.

TABLE I

ELECTROMAGNETIC TORQUE PERFORMANCE AND LOSSES FOR MACHINES WITH/WITHOUT PMS (400 RPM)

Symbol	Parameters	Unit	F1A3 HSSPMM	DC-SFM
T_{ave}	Average torque	mm	0.95	0.34
T_{ripple}	Torque ripple	%	27.96	113.22
P_{cu}	Copper loss	W	60	60
P_{rloss}	Rotor iron loss	W	0.247	0.253
P_{sloss}	Stator iron loss	W	1.285	1.508

Since the novel PM machine locates PMs and wound field coils in one slot, the PM volume needs to be fixed and assumed to be the same as the conventional HSSPM to ease the design optimization. Besides, the slot areas, excited currents of armature and field coils are uncertain, and thus, the ratio of field current density to armature current density needs to be considered as a variable parameter during the optimization. Furthermore, the stator outer radius, stack length, air-gap length, and copper loss of the F1A3 HSSPMM are fixed during optimization and same as the conventional HSSPMM. The iron loss in the HSSPMM is quite small (<2W) when compared with the copper loss (60W), and the PMs only have slightly influence on the iron loss. Thus, the iron loss will not be considered during the design process. The losses of the machine are listed in Table I as well, and the design details of the obtained machine are listed in Table II.

TABLE II

DESIGN PARAMETERS OF F1A3 HSSPMM

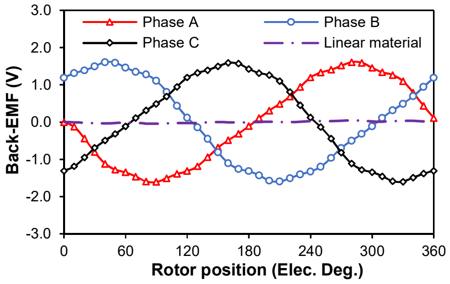
Symbol	Parameters	Unit	F1A3 HSSPMM
R_{SO}/R_{SI}	Stator outer/inner radius	mm	45/20.14
l_{stack}	Stack length	mm	25
G	Aig-gap length	mm	0.5
H_{PM}	PM height	mm	3.99
V_{PM}	PM volume	mm^3	6396
$Br/\mu r$	PM N38SH at 20 °C		1.2T/1.05
H_{BI}	Back-iron thickness	mm	4.23
$\Theta st/\theta rt$	Stator/rotor pole arc	Mech. Deg.	6.78/15.68

III. INFLUENCE OF MAGNETIC SATURATION

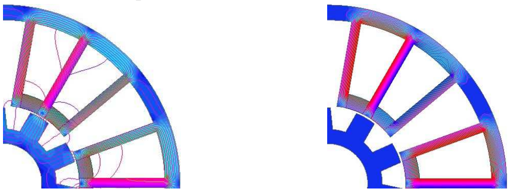
Based on the machine operation principle, the F1A3 HSSPMM should have negligible open-circuit back-EMF since the PM flux is shunted in the stator and the amplitude of the open-circuit back-EMF is negligible, as shown in Fig. 3 (a). Considering the assumption of non-saturation, linear material has been chosen for the stator and rotor and the machine is simulated with 2D FEM. Hence, the PM flux is shunted in the stator as shown in Fig. 4(c), which has proved the operation principle when DC field current is zero. Fig. 4(b) shows that the stator tooth between adjacent PMs is severely magnetically saturated when the lamination iron material of machine stator and rotor is non-linear. In that case, a part of the flux produced by PM will be leaked to the other direction which can get through to the rotor via air-gap.

However, in reality, Fig. 4(b) gives the true PM flux path and the leaked flux path is followed in black which is shown in Fig. 3(b), since the stator and rotor iron materials are laminated steel (non-linear material). It is found that the amplitude of the back-EMF waveforms for three phases is non-zero, as shown in Fig. 4(a) since the PM flux is leaked with rotor varies with the rotation of salient rotor, and non-zero back-EMF is produced.

Due to the stator wound DC coils, the flux is adjustable with the variable DC field current. Fig. 5 shows the fundamental magnitude of back-EMF variation with increasing DC field current for the machine with both linear and non-linear material stator and rotor. The back-EMF will increase linearly from zero with the increasing DC field current when the magnetic property of stator and rotor is linear. When the stator and rotor have non-linear material, the variation tendency of back-EMF magnitude is much more complicated due to magnetic saturation.



(a) Open-circuit back-EMF waveforms



(b) Non-linear material (c) Linear material

Fig. 4. Open circuit back-EMF waveforms and flux line and flux density distributions of F1A3 HSSPMM (400 rpm, I_{dc} = 0A).

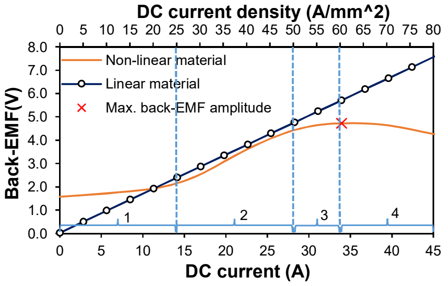
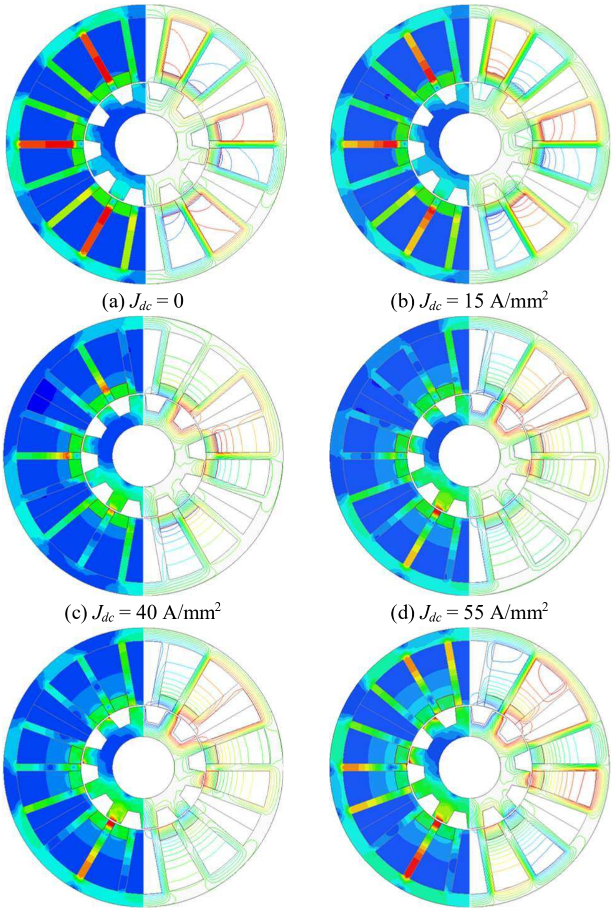


Fig. 5. Variation of phase back-EMF magnitudes of the F1A3 HSSPM machine with non-linear and linear materials for stator and rotor with the increasing DC current and DC current density.

When the current excitation is zero, the large PM flux leakage caused by stator magnetic saturation results in the significant back-EMF. Besides, Fig. 6(a) proves that the severe magnetic saturation in the stator tooth between two adjacent PMs. The back-EMF magnitudes increase slightly with the DC current density when it is lower than 25 A/mm^2 (Fig.4, region 1), indicating that the DC field current reduces the saturation caused by PMs. Fig. 6(b) gives the flux distribution at DC current density of 15 A/mm^2, the magnetic saturation on the stator tooth still remains, but obviously alleviated compared with that at no current excitation condition, Fig. 6 (a). For the DC current density from 25 to 50 A/mm^2 (Fig. 4, region 2), the flux produced by DC excitation will contribute more significantly to the phase back-EMF. Furthermore, the increasing tendency of this current range is quite similar to the machine with linear material stator/rotor, and the stator of the machine is hardly saturated, which can be proved in Fig. 6(c). In region 3 of Fig.4, the raising ratio tends to become slow. Combined with Fig. 6(d), that mild tendency can be explained by the saturation of stator flux path towards rotor. When the DC current density achieves 60 A/mm^2, the machine has no shunted PM flux as shown in Fig. 6(e), and achieved the maximum value of the back-EMF magnitude. Finally, in region 4 of Fig. 4, the machine tends to magnetically saturation again since the machine is over excited as can be proved in Fig. 6(f). Besides, the flux path produced by DC current excitation is dominated when the DC current density is larger than 60 A/mm^2. Generally, the initial magnetic saturation can be reduced by adding DC field current, and the machine will be saturated again with the large DC field excitation. When the machine is over saturated, the fundamental magnitude of the back-EMF will be reduced.



(a) J_{dc} = 0 (b) J_{dc} = 15 A/mm^2

(c) J_{dc} = 40 A/mm^2 (d) J_{dc} = 55 A/mm^2

(e) J_{dc} = 60 A/mm^2 (f) J_{dc} = 80 A/mm^2

Fig. 6. Open-circuit flux density distributions of F1A3 HSSPMM with different DC current density.

IV. MACHINE TEST RESULTS AND INFLUENCE OF ROTOR ECCENTRICITY

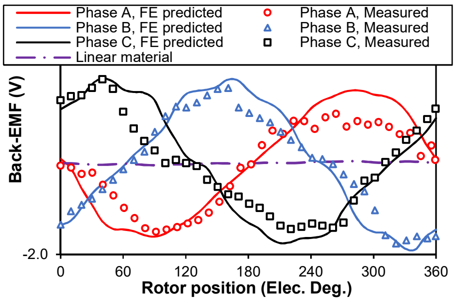
A prototype F1A3 HSSPMM is shown in Fig. 7 to validate the optimization principle and the influence of magnetic saturation. The stator and rotor are made from laminated steel, and the frame is made from aluminium. NdFeB (remanence B_r=1.2T, and relative permeability u_0=1.05) is chosen to be the material of magnets.

The open-circuit experiment is taken at the rotor rotating speed of 400 rpm. The measured and FE predicted back-EMF waveforms without DC current excitation are shown in Fig. 8. The test results have validated the large PM flux-leakage due to the existence of back-EMF. The leaked PM flux coincidentally passed in the main magnetic path since the stator slot opening PM structure makes the leaked flux though the air-gap, as described in detail in section III.

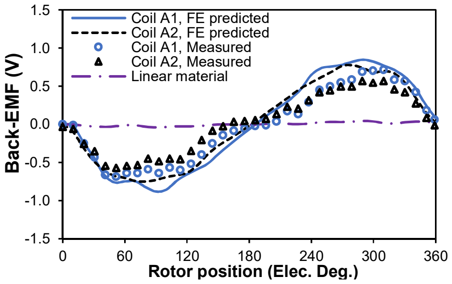
Moreover, it is observed during the experiment that the measured waveforms and amplitudes of 3-phase back-EMFs are different, and further, those of individual coils in the same phase are different as well. In addition, the back-EMF waveforms are asymmetric, indicating the prototype machine might exhibit rotor eccentricity. Based on the measured results, 2D FEA is employed to determine the approximate position of the rotor. The FEA predicted and measured back-EMF waveforms are shown in Fig. 8. The amplitudes of measured back-EMFs for coils B1 and C1 are almost twice larger than those of B2 and C2, respectively, as shown in Fig. 8(c) and Fig. 8(d). Thus, the rotor of the prototype machine exhibits static eccentric towards the centre of B1 and C1 of almost 50%. Since the measured back-EMF of coil A1 is slightly larger than that of coil A2, as shown in Fig. 8(b), the rotor eccentricity is found to be further 6% towards coil A1 according to the amplitude difference. The predicted and measured waveforms are of a good agreement although not perfectly the same since the exact eccentric position of the rotor is not clear and even 3D rotor eccentricity may exist. Moreover, the rotor shaft may also be slightly dynamically eccentric. Nevertheless, the FEM predicted and measured back-EMF waveforms and also their good agreement confirms the significant influence of rotor eccentricity.

(a) 6-pole stator (b) 10-pole rotor

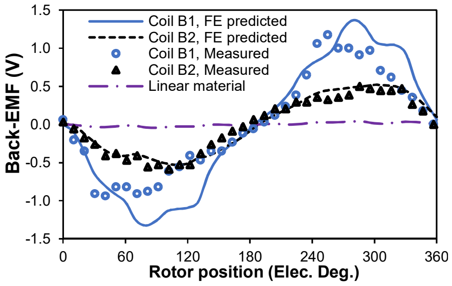
Fig. 7. F1A3 HSSPMM prototype with 6/10 stator/rotor poles.



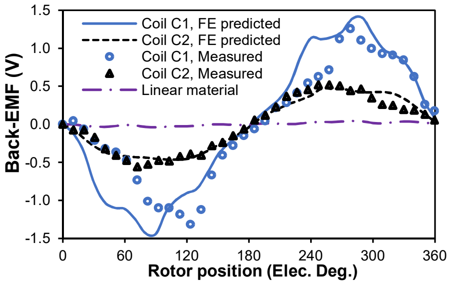
(a) Phase back-EMFs



(b) Coil back-EMFs for phase A



(c) Coil back-EMFs for phase B



(d) Coil back-EMFs for phase C

Fig. 8. Comparison of measured and FEM predicted back-EMF waveforms for non-linear material stator and rotor with the rotor shaft eccentricity of 50% towards to the centre between coils B1 and C1, and 6% towards the centre of coil A1 (400rpm, $I_{dc} = 0$A).

It is worth mentioning that when the machine is on load, the rotor eccentricity only has slight influence on the average electromagnetic torque, and the FEM predicted electromagnetic torques of the machines with/without rotor eccentricity are shown in Fig. 9, their average values being 1.01Nm and 0.95Nm, respectively.

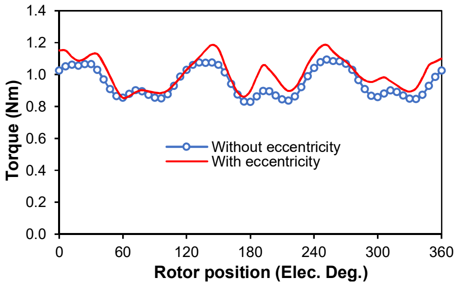


Fig. 9. Electromagnetic torques for HSSPMMs with/without rotor eccentricity.

V. CONCLUSION

In this paper, a novel HSSPMM is proposed and the operation principle of the machine is introduced. The influence of magnetic saturation and rotor eccentricity on the electromagnetic performance is investigated, with particular emphasis on back-EMF. It is found that the open-circuit back-EMFs of the machine exist, indicating the stator is severely magnetically saturated and large PM leakage flux exists. The prototype machine test results have verified the existence of stator magnetic saturation. The predicted and measured unbalanced phase and coil open-circuit back-EMF waveforms show the prototype machine has rotor eccentricity and the eccentric rotor position is determined according to the measured amplitudes of coil EMFs. Good agreements exist between the 2D-FE predicted and measured results of open-circuit back-EMFs.

REFERENCES

[1] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. B. Ahmed, and M. Lécrivain, “Hybrid excitation synchronous machines: energy-efficient solution for vehicles propulsion,” *IEEE Trans. on Vehicular Tech*., vol. 58, no. 5, pp. 2137-2149, June 2009.

[2] Z. R. Zhang, Y. G. Yan, S. S. Yang and Z. Bo, "Principle of Operation and Feature Investigation of a New Topology of Hybrid Excitation Synchronous Machine," in *IEEE Trans. on Magn.*, vol. 44, no. 9, pp. 2174-2180, Sept. 2008.

[3] H. Hua and Z. Q. Zhu, "Novel hybrid-excited switched-flux machine having separate feld winding stator," in *IEEE Trans. on Magn.*, vol. 52, no. 7, pp. 1-4, July 2016.

[4] K. Nakamura, K. Murota, and O. Ichinokura, “Characteristics of a novel switched reluctance motor having permanent magnets between the stator pole-tips,” *European Power Electronics and Appl. Conf.*, 2-5 Sept. 2007.

[5] P. Andrada, B. Blanqué, E. Martínez, M. Torrent, “New hybrid reluctance motor drive,” *Int. Conf. On Elec. Mach. (ICEM)*, 2012.

[6] I. A. A. Afinowi, Z. Q. Zhu, Y. Guan, J. C. Mipo, and P. Farah, “Hybrid-excited doubly salient synchronous machine with permanent magnets between adjacent salient stator poles,” *IEEE Trans. on Magn.*, vol. 51, no. 10, 2015.

[7] Z. Q. Zhu, I. A. A. Afinowi, Y. Guan, J. C. Mipo, and P. Farah, “Hybrid-excited stator slot permanent magnet machines—influence of stator and rotor pole combinations,” *IEEE Trans. on Magn.*, vol. 52, no. 2, 2016.

[8] Y. J. Zhou and Z. Q. Zhu, “Comparison of wound-field switched-flux machines,” *IEEE Trans. on Ind. Appl.*, vol.50, no. 5, pp. 3314-3324, 2014.

[9] R. L. Owen, Z. Q. Zhu, and G. W. Jewell, “Hybrid-excited flux-switching permanent-magnet machines with iron flux bridges” *IEEE Trans. On Magn.*, vol. 46, no. 6, pp.1726-1729, 2010.

[10] Z. Q. Zhu and J. T. Chen, “Advanced flux-switching permanent magnet brushless machines,”, *IEEE Trans. on Magn.*, vol.46, no.6, pp.1447-1453, 2010.

[11] E. Hoang, M. Lecrivain, and M. Gabsi, "A new structure of a switching flux synchronous polyphased machine with hybrid excitation," *European Conf. on Power Electron. and Appl.,* 2007, pp.1-8.

[12] E. Hoang, M. Lecrivain, S. Hlioui, and M. Gabsi, “Hybrid excitation synchronous permanent magnets synchronous machines optimally designed for hybrid and full electrical vehicle,” *8th Int’l Conf. on Power Electron.-ECCE Asia*, 2011, pp. 153-160.

[13] E. Sulaiman, T. Kosaka, N. Matsui, and M. Z. Ahmad, “Design study on high torque and high power density hybrid excitation flux switching synchronous motor for HEV applications,” *IEEE Int’l Power Engineering and Optimization Conf.*, Melaka, Malaysia, 2012, pp. 333-338.