Development of a New Flux Switching Transverse Flux Machine with the Ability of Linear Motion

Chengcheng Liu, Shaopeng Wang, Youhua Wang, Gang Lei, Youguang Guo, and Jianguo Zhu

***Abstract*—This paper proposes a new rotary flux switching transverse flux machine with the ability of linear motion (FSTFMaLM), in which both the stator and the rotor cores are made by using soft magnetic composite (SMC) materials. With the special design pattern, for the rotary motion model, the proposed machine can combine both the advantages of the flux switching permanent magnet machine (FSPMM) and the transverse flux machine (TFM). It can output with relatively high torque density, and as there is no windings or the magnets on the rotor cores, the proposed machine can operate in the high speed region to improve the output power. With the adoption of the SMC materials, the manufacturing of this machine can be quite easy. By stacking the rotor core together and prolong it with the determined length in the axial direction, in addition with the special control algorithm, the proposed machine can have the ability of the linear motion. In this paper, the operation principle of this machine has been explained and the design methods are also presented. To seek the better performance, the main dimension of the machine is optimized, and for the performance evaluation, the finite element method (FEM) is adopted. The proposed machine can be used for the electric driving systems, robotic systems or other applications where the linear motion ability is required.**

***Index Terms*—Flux switching, linear motion, high torque density, soft magnetic composite (SMC), transverse flux machine.**

I. Introduction

THE electrical machines with the not only rotary ability but also the linear motion ability can be used in several drive applications to replace the combination of a rotary electrical machine and a linear machine, e.g. in the servo actuators for gearbox or the integrated actuations of basic active wheels on board of electric and hybrid vehicles [1],[2]. In the electric and hybrid vehicles, for the performance optimization the two speed or three speed gearbox is required, since in the low speed region the torque of the driving system needs to be enlarged several times to provide the electric vehicle with a high output torque, while for the high speed region, the high power is more important [3]. In such applications, the rotary ability of the electrical machine is the main task. However, if the electrical machine can provide with the linear motion ability to assist the gearbox to work in different gear rations, the complexity of the whole system and therefore the total cost of the drive system can be reduced.

With the permanent magnets (PM) installed in the stator of the electrical machine, the flux switching permanent magnet machine (FSPMM) can output very high torque density. Since there is no winding or magnets on the rotor, the mechanical robust of the FSPMM is very high [4], [5]. In the past decades, the improvement of the performance of the FSPMM with the different methods include design with different stator core structures, different hybrid excitation methods, different magnet flux path, optimization, and etc.[6]-[8]. Compared with the interior permanent magnet machines, the FSPMM has shown its advantages and it is a potential machine for the electric vehicle application and other high performance applications [9], [10]. With the adoption of the global ring winding, the transverse flux machine (TFM) is another machine which was proposed by Weh [11]. Compared with other electrical machines, the TFM has the merits of the higher torque density [12-18]. However, with the complex magnetic flux path, the manufacturing of this kind of machine is a great issue. By using the soft magnetic composite (SMC) materials, the flux switching transverse flux machine (FSTFM) has been proposed in our previous work [19], and this new machine has shown the good performance by taking not only the advantages of the flux switching machine but also the transverse flux machine. With the adoption of the SMC materials, the manufacturing of the flux switching transverse flux machine is quite easy. Moreover, as the SMC material has lower core loss under higher frequency compared with the silicon steels, this machine is expected to have good performance.

In this paper, based on the main topology of the FSTFM, a new FSTFM with the ability of linear motion (FSTFMaLM) is proposed, which can not only have the ability of rotary motion but also the linear motion ability. It can be used for the electric

Manuscript was submitted for review on 03, May, 2018.

This work was supported in part by the National Natural Science Foundation of China under project 51877065 and Hebei Province Education Department Youth Talent Leading Project under grant BJ2018037.

Chengcheng Liu, Shaopeng Wang and Youhua Wang are with State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology and Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability of Hebei Province, Hebei University of Technology, Tianjin, 300130, China (2016020@hebut.edu.cn, 522396000@qq.com, wangyi@hebut.edu.cn)

Gang Lei, and Youguang Guo are with the School of Electrical and Data Engineering, University of Technology Sydney, NSW 2007, Australia, (gang.lei@uts.edu.au, youguang.guo@uts.edu.au)

Jianguo Zhu is with school of electrical and information engineering, University of Sydeny, NSW 2007, Australia, (jianguo.zhu@sydney.edu.au)

Digital Object Identifier 10.30941/CESTEMS.2018.00049

drive systems for the electric vehicle or the hybrid vehicle to reduce the complexity of the gearbox system, or it can be used in the robotic system or other applications where both the rotary motion and linear motion ability are required.

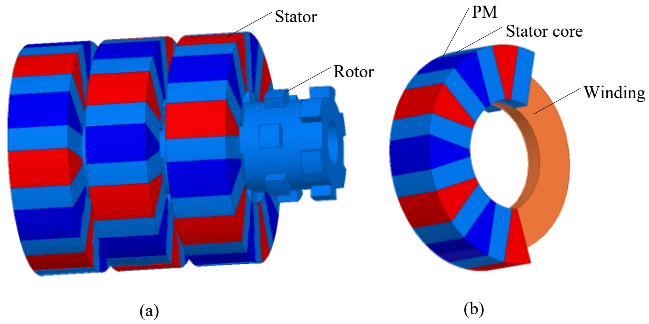


Fig. 1. Main topology of the new FSTFMaLM, (a) the complete magnetic structure of the machine, and (b) one stator core module of the machine.

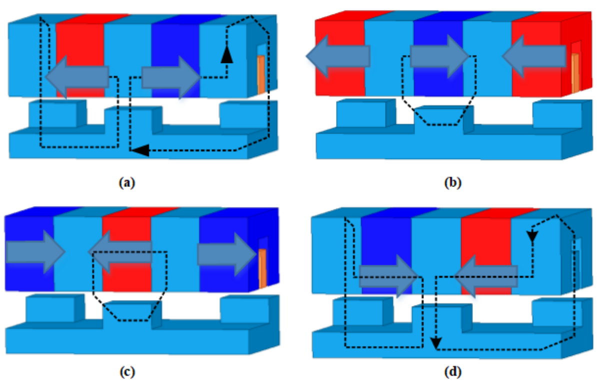


Fig. 2. Main flux path of the new FSTFMaLM in rotary model, (a) PM flux (positive maximum), (b) PM flux (zero), (c) PM flux (zero), and (d) PM flux (negative maximum)

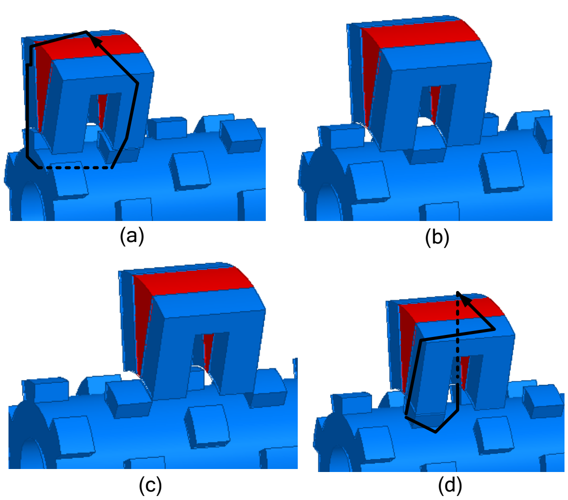


Fig. 3. Main flux path of the new FSTFMaLM in linear motion model, (a) PM flux (positive maximum), (b) PM flux (zero), (c) PM flux (zero), and (d) PM flux (negative maximum).

II. Topology and Operation Principle of the Novel FSTFMaLM

Fig. 1 illustrates the main topology of the new FSTFMaLM. It can be seen that this machine is composed of the three stator core modules and one rotor core module. For the stator module, it is quite similar to the stator cores of the 3D transverse flux flux switching permanent magnet machine (3D TFFSPMM) in [15]. For one stator module, it is composed of 12 stator cores and 12 magnets, and all the magnets are magnetized along the

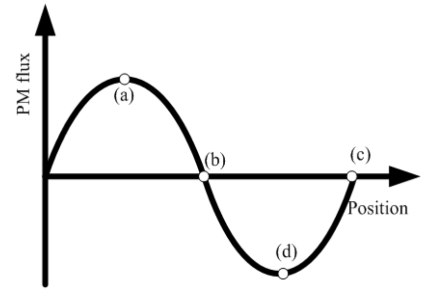


Fig. 4. PM flux linkage of the FSTFMaLM in rotary model and linear motion model against the rotor position.

circumferential direction while the adjacent magnets are magnetized in the opposite direction. The stator cores and magnets can form the whole cylinder and the winding is installed in the middle of the stator slot. The distance between the adjacent stator modules equals the distance between the adjacent rotor teeth in the axial direction. To form the three-phase operation in the rotary model, the adjacent stator modules have been shifted by 120 electrical degrees with each other. The rotor core of this machine is similar to that of the 3D TFFSPMM, but it was prolonged with one rotor core to form the linear motion ability.

The operation principle of this machine can be referenced as that of traditional flux switching permanent magnet machine in [4]. However, the flux path loop of the new machine is very complex and quite different when compared with the traditional FSPMM, which can be shown in Fig. 2 and Fig. 3. As shown in Fig. 2(a), at this position the PM flux will flow on the clockwise direction and the PM flux crossing the winding can reach the positive maximum. When the rotor moves along the right direction and reaches the position as shown in the Fig. 2(b), the PM flux linkage crossing the winding will be zero. The PM flux linkage crossing the winding with the relationship with the rotor position can be found in Fig. 4. Compared with the rotary motion model, the change of the PM flux of the new FSTFMaLM is illustrated in Fig. 3. It can be seen that when the rotor teeth are aligned with the stator teeth, the PM flux linkage will be the positive maximum or the negative maximum, while when the rotor is moved with the rotor teeth aligned with the stator slots, the PM flux linkage of the machine will be zero. The change of the PM flux linkage with the rotor axial position can be seen in Fig. 5 as well. As shown, both the rotary motion and the linear motion of the machine are worked with the flux switching principle.

Fig. 5 shows the operation model of the new FSTFMaLM in both the rotary model and the linear motion model. In this figure, when the each part of block R is under block N or block S, the PM flux linkage of the winding can achieve the maximum one. When block R is under the left side of block N, the PM flux linkage will be the positive maximum one, or it will be the negative maximum one. Fig. 5(a) shows the FSTFMaLM in the initial position. For the linear motion it can be seen in Fig. 5(b) that all the three windings will achieve the

PM flux linkage of zero at the same position. Specifically the overall output of the force for this machine will be similar to that of single phase linear machine. As illustrated in Fig. 5(c), the FSTFMaLM is a standard three phase FSTFM in the rotary motion model. The work state of the FSTFMsLM in the rotary motion and the linear motion can be explained by Fig. 5(d).

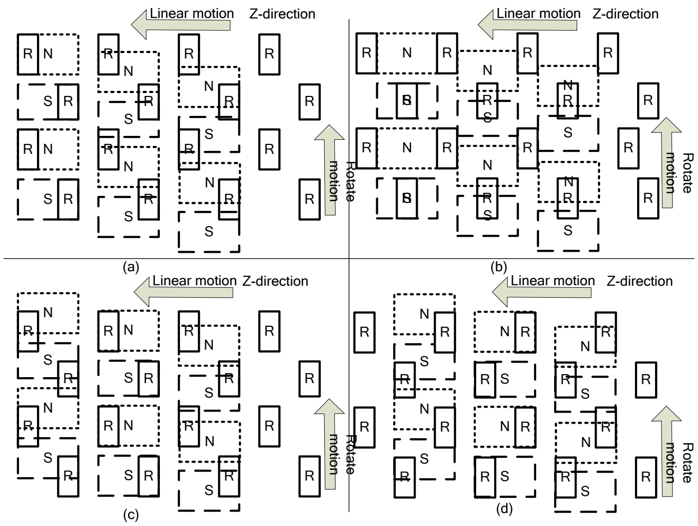


Fig. 5. Operation model of the new FSTFMaLM in the rotate model and the linear model.

Base on the above analysis, the PM flux linkage of the windings A, B, and C can be expressed by,

$$\begin{aligned}\psi_A &= \psi_{PM}\cos(P\theta)\cos(2\pi z/l)\\ \psi_B &= \psi_{PM}\cos(P\theta-2\pi/3)\cos(2\pi z/l)\\ \psi_C &= \psi_{PM}\cos(P\theta+2\pi/3)\cos(2\pi z/l)\end{aligned} \quad (1)$$

where ψ_{PM} is the maximum PM flux of the machine, P the number of pole pairs of the machine in the rotary motion model, θ the motion angle of the rotor, z the motion position of the rotor in the axial direction, and l the distance between the adjacent rotor pole in the same axial axis. When the machine is in the rotary motion model, then the induced voltage can be calculated by,

$$\begin{aligned}e_A &= -P\omega\psi_{PM}\sin(P\omega t)\cos(2\pi z/l)\\ e_B &= -P\omega\psi_{PM}\sin(P\omega t-2\pi/3)\cos(2\pi z/l)\\ e_C &= -P\omega\psi_{PM}\sin(P\omega t+2\pi/3)\cos(2\pi z/l)\end{aligned} \quad (2)$$

where ω the rotor rotary speed and t the time. And its electromagnetic power can be calculated by,

$$P_{em} = 1.5 * P\omega\psi_{PM} I_q A_c k_f \left|\cos(2\pi z/l)\right| \quad (3)$$

where I_q is the q axis current density, A_c the cross section area of the winding, and k_f the slot fill factor. It can be known that the power of the FSTFMaLM is related by the rotor position in the axial direction. When the machine is in the linear motion model, the induced voltage can be calculated by,

$$\begin{aligned}e_A &= -(2\pi/l)v\psi_{PM}\cos(P\theta)\sin(2\pi vt/l)\\ e_B &= -(2\pi/l)v\psi_{PM}\cos(P\theta-2\pi/3)\sin(2\pi vt/l)\\ e_C &= -(2\pi/l)v\psi_{PM}\cos(P\theta+2\pi/3)\sin(2\pi vt/l)\end{aligned} \quad (4)$$

where the v is the speed for the linear motion. And its power can be calculated by,

$$P_{em} \approx 2.43 * (2\pi/l)v\psi_{PM} I_q A_c k_f \sin^2(2\pi vt/l) \quad (5)$$

As shown in the above equations, for the rotary motion model, when the rotor is in the position of z equal to *kl/2*, where *k* is the integer number, the torque of machine will be the standard torque, the same as that of 3DFTFFSPMM [15]. When the rotor is in the position of *z* equal to *(2k+1)/4*l, the torque will be zero. When *k* equals the other number the torque of the machine will decrease with certain degree. As for the linear motion model, there is no requirement for the rotor position in the rotary position. However, the phase of the back *emf* will change with the different rotor position. The output torque of the FSTFMaLM at the rated state is 1.55 Nm, and the output force of the new FSTFM at the rated state is 25 N. The main dimensions of this machine are optimized to achieve higher torque and force, and its main dimensions are listed in the follow table.

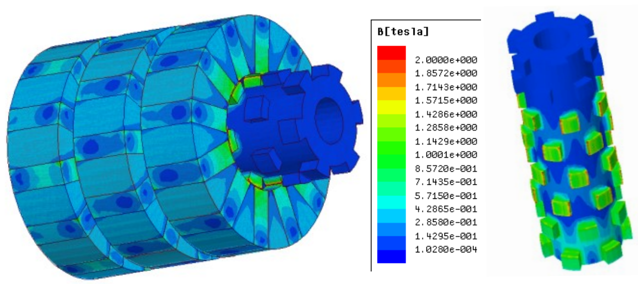
TABLE I
MAIN DIMENSIONS OF NEW FSTFM

Parameter name	Symbol	Value	Unit
Shaft radius	R_{shaft}	9.5	mm
Stator outer radius	R_{so}	47.5	mm
Stator inner radius	R_{si}	25.65	mm
Height of stator yoke	H_{sy}	5.7	mm
Width of stator tooth	W_{sty}	8.55	mm
Air gap length	L_{gap}	0.5	mm
Effective axial length	L_{axial}	27	mm
Length of rotor tooth	L_{rt}	4.75	mm
Length of stator tooth in radial direction	L_{st}	10.3	mm
Length of PM yoke in radial direction	L_{myr}	14.6	mm
Number of coil turns	N_c	107	
Slot fill factor		0.6	

III. MAGNETIC FIELD ANALYSIS AND MAGNETIC PARAMETER ANALYSIS OF THE NOVEL FSTFMALM

The analysis of the magnetic field and the magnetic parameter is very important for the performance analysis of the electrical machines. Moreover, for the accurate magnetic analysis of the 3D flux machine with the nonlinear magnetic materials adopted, the finite element method (FEM) is the best method. In this paper, the commercial FEM software ANSYS is used for the magnetic analysis.

Fig. 6 illustrates the no load magnetic flux density distribution of the new FSTFMaLM, and Fig. 7 shows the no load air gap flux density in the radial direction of the new FSTFMaLM. It can be seen that the maximum flux density in the stator teeth and the rotor teeth can achieve more than 1.2 T, and the maximum air gap flux density can achieve about 1.1 T. As shown, the flux leakage is existed in the machine, resulted by the complex 3D magnetic flux circuit and strong flux coupling effect between the rotary motion and linear motion state. For the permanent magnet machine with the NdFeB magnets and silicon steels, to obtain the air gap flux density of 1.1 T is not a difficult work. However, the magnets used in this novel FSTFMaLM is the ferrite magnet in which the residual magnetic flux density is only 0.4 T. Moreover, the SOMALOY 500^{TM} is used for the magnetic cores of the machine, and the average permeability of the SOMALOY 500^{TM} is only about 200, which is much lower than that of silicon steels. With the adoption of the SMC material and the ferrite magnets, not only the cost of the machine can be reduced, but also the power loss will be reduced when it is operated in the high frequency.



(a) (b)

Fig. 6. No load flux density distribution of the novel FSTFMaLM, (a) stator core, and (b) rotor core

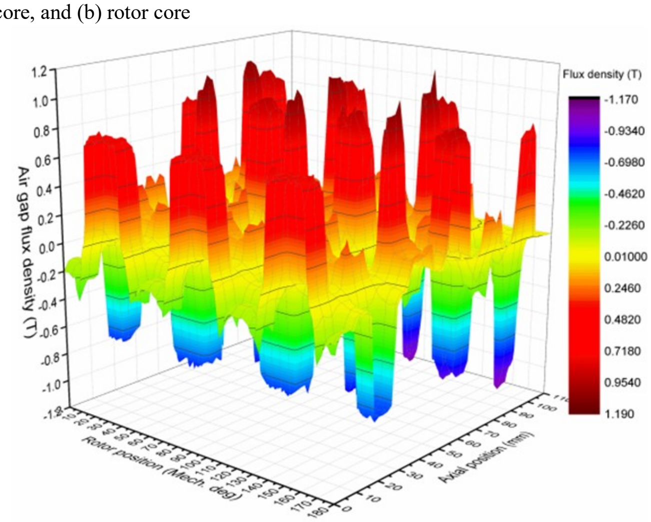
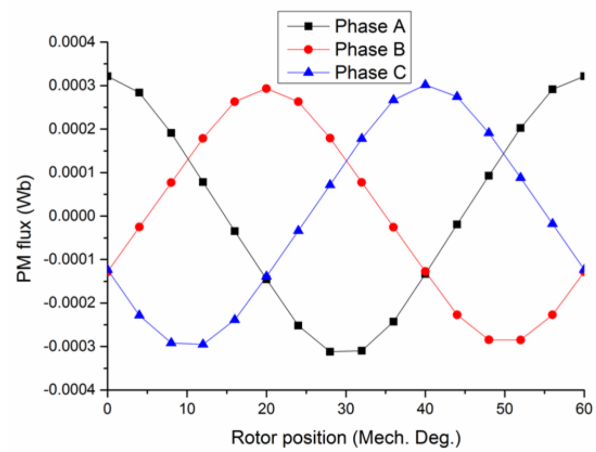
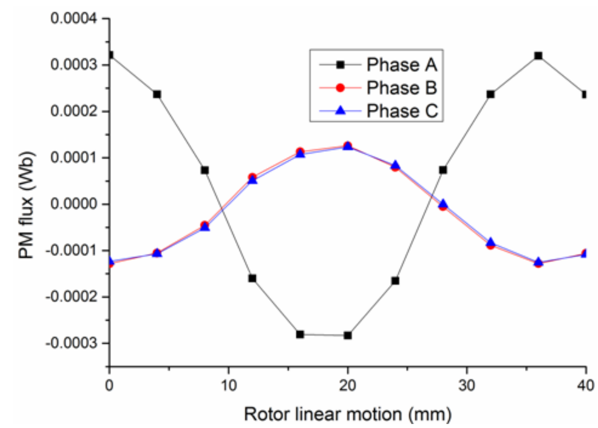


Fig. 7. No load air gap flux density distribution of the novel FSTFMaLM

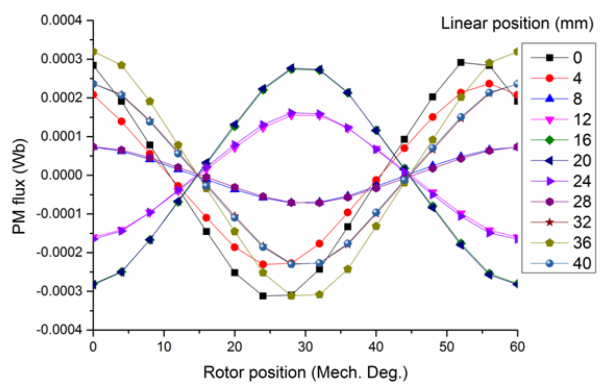
Fig. 8 illustrates the PM flux linkage per turn of the novel FSTFMaLM. It can be seen that when the rotor is in the position of z equal to 0 mm, the PM flux linkage of the three phase windings are shown and the adjacent phases have the phase shift of 120 electrical degrees with each other. As shown in Fig. 8(b), the flux linkage of winding A has the same peak value when compared with its value in the rotary model. For the other two windings, it can be seen that the peak value is about half of that of their windings in the rotary model. Windings B and C have the same phase and they are opposite to phase A. for the linear motion state, the phase A, B and C are the same phase. For the complete machine, there is 9 stacks and the symmetrical three phase for the linear motion state can be formed. Figs. 8(c) and 8(d) show the PM flux linkage of winding A when it is in the rotary model and in linear motion model, with different linear positions and rotary positions, and these results can match the deduced equation (1). For windings B and C, their PM flux linkages in the rotary model and linear motion model with different linear positions and rotary positions are shown in Fig. 9, which also match the principle analysis results.



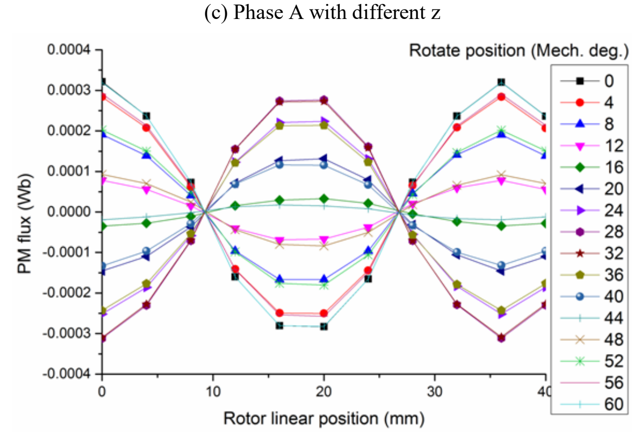
(a) Phases A, B and C when z equals 0 mm



(b) Phases A, B and C when θ equals 0 deg.

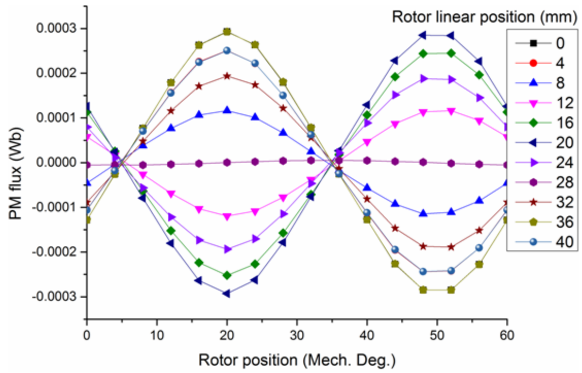


(c) Phase A with different z

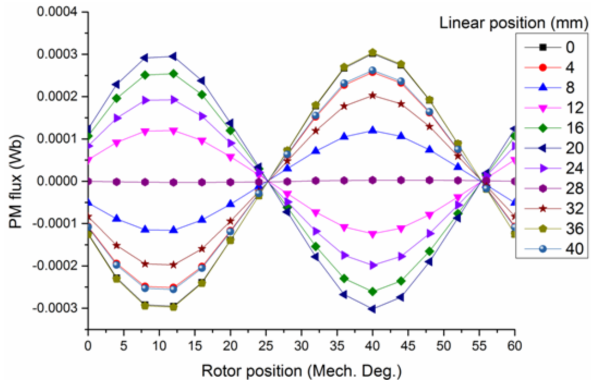


(d) Phase A with different θ

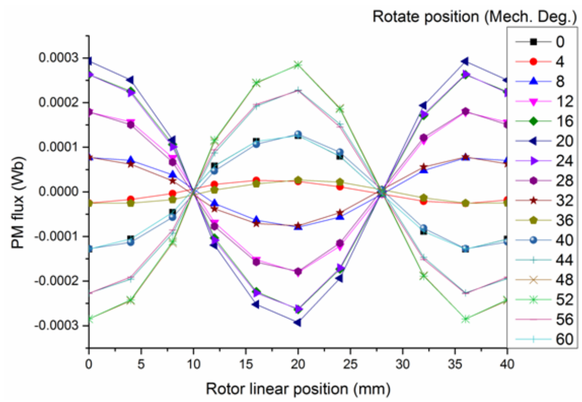
Fig. 8. PM flux linkage per turn of the novel FSTFMaLM..



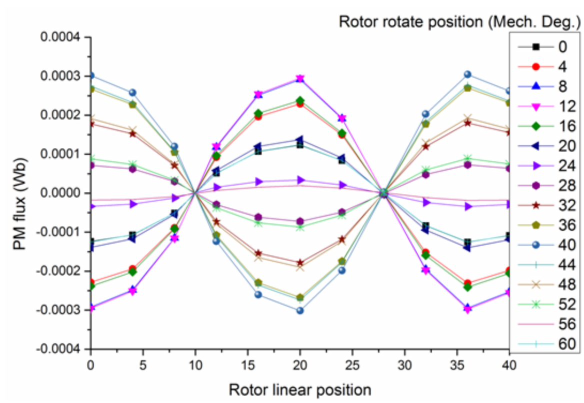
(a) Phase B in rotary model with different z



(b) Phase C in rotary model with different z



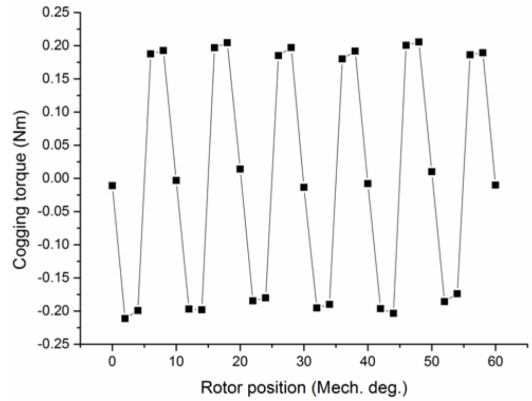
(c) Phase B in linear motion model with different θ



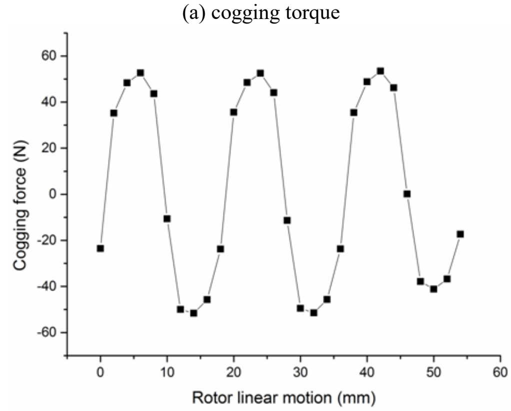
(d) Phase C in linear motion model with different θ.

Fig. 9. PM flux linkage per turn of the novel FSTFMaLM,

Fig. 10(a) illustrates the cogging torque of the novel FSTFMaLM, which is calculated by the virtual work method, and Fig. 10(b) illustrates the cogging force of the novel FSTFMaLM. When compared with the 3DFTFFSPMM in [15], it can be seen that the cogging torque is the same as the that of 3DFTFFSPMM, as the magnetic couple of the adjacent stator model of the novel FSTFM is very weak, as shown in Fig. 11.

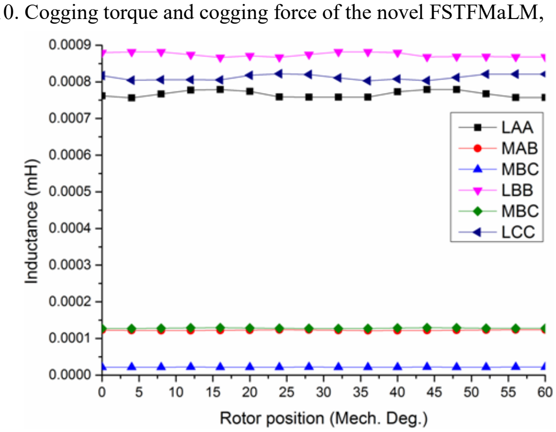


(a) cogging torque

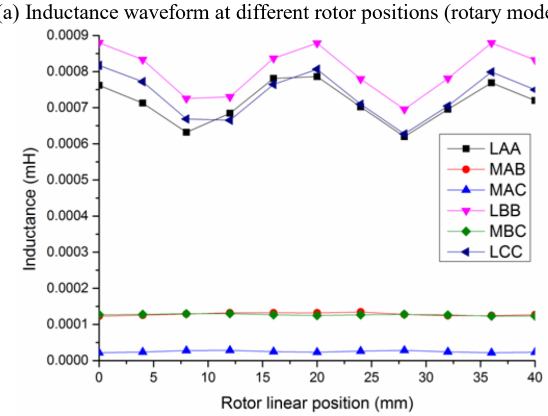


(b) cogging force

Fig. 10. Cogging torque and cogging force of the novel FSTFMaLM,



(a) Inductance waveform at different rotor positions (rotary model)

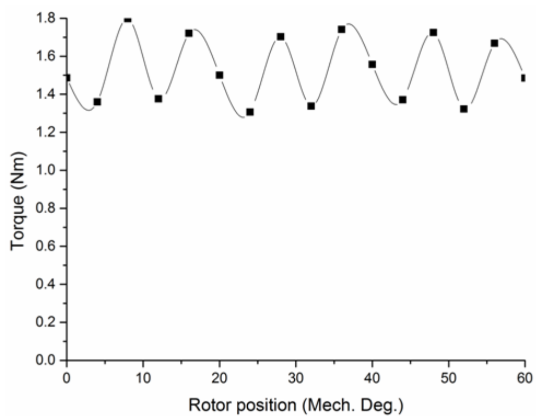


(b) Inductance at the different rotor positions (linear model)

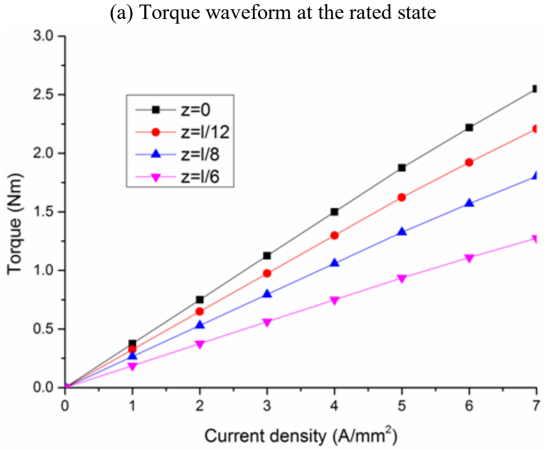
Fig. 11. Inductance of the novel FSTFMaLM.

IV. Performance Evaluation of the Novel FSTFMaLM

The main target of the electrical machine is to output force or torque, thus the output torque or force can represent the most important performance of the electrical machines. Based on the principle analysis, it can be known that the output torque of the novel FSTFMaLM will be varied with the different axial positions of the rotor, and for some determined positions the output torque of the machine will be zero, and this should not happen when the machine needs to have the rotary ability. As shown in the Fig. 12, the torque of the novel FSTFMaLM at the rated current density of 4 A/mm^2, is about 1.5 Nm, and Fig. 12(b) shows the average torque of the novel FSTFMaLM with the different current density and different axial position of the rotor. Based on these analysis, it can be seen that when the rotor is moved to the determined axial position, it can not only provide the motor with the axial force but also the flux weakening ability, which can help the machine to operate in the higher speed without the additional demagnetized d axis current.



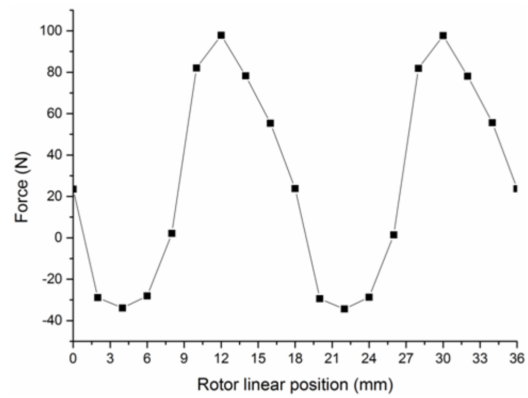
(a) Torque waveform at the rated state



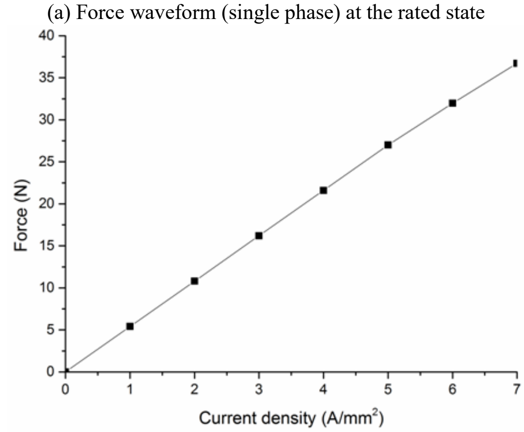
(b) Averaged torque at the different z position.

Fig. 12. Torque of the novel FSTFMaLM.

As mentioned in section II, with this kind of design in this paper, when the machine works in the linear motion model, the three windings of the machine are in the same phase, thus for the output force it will show the one phase motor performance. Fig. 13 shows the force of the novel FSTFMaLM. It can be seen that the force ripple is very high, and even for some positions it is a negative value, which is resulted by the high cogging force as shown in Fig. 10(b). To eliminate the force ripple, there is a great number of methods. However for the machine developed in this paper, the axial force is only the assist force, thus we do not take the special measure to reduce it. While, for some applications where the low force ripple is required, the designed FSTFMaLM can be designed in module way to have three same machines designed to assembly in the axial way to provide the three phase shift for the linear motion model. The power factor of the designed FSTFMaLM at the rated state is about 0.5, however that for the traditional outer rotor TFM with SMC cores is about 0.62 [14]. The main reason is that the flux leakage is high in the stator PM TFM if compared with the rotor PM TFM.



(a) Force waveform (single phase) at the rated state



(b) Averaged force with different input current density.

Fig. 13. Force of the novel FSTFMaLM.

V. Conclusion

In this paper, a novel FSTFMaLM with both the rotary ability and linear motion ability is proposed. As the flux switching operation principle and the transverse flux are applied, and with the adoption of the SMC materials, the output torque and force of this machine is quite high though the ferrite magnet is used to provide the PM flux. By designing the rotor with the special structures and the determined distance between the adjacent stator cores, the designed machine can have the ability of the linear motion. The PM flux and the back *emf* equations of this machine in both the linear motion and the rotary motion are deduced based on the analysis of the operation principle.

By using the FEM method, the magnetic field and the magnetic parameters of the developed machine were analyzed. It can be seen that with the special design, the magnetic load is relatively high though the ferrite magnets are used to produce the PM flux and the average permeability of the SOMALOY 500^{TM} is only about 200. The calculated PM flux linkages can match the PM flux linkage equations based on principle analysis. The designed FSTFM has the same cogging torque and the torque performance compared with that of the 3DFTFFSPMM. As for the force, the waveform of the new FSTFMaLM is not good, while for the average value it can achieve the same force ability when compared with the other linear machines. The developed novel FSTFMaLM can be designed with some other forms to achieve the low force ripple to meet the performance requirement of the different applications.

REFERENCE

[1] P. Bolognesi, O. Bruno, and L. Taponecco, "Dual-function wheel drives using rotary-linear actuators in electric and hybrid vehicles," in *Proc. 35th IECON Conf.*, Porto, Portugal, Nov. 2009, pp. 3916–3921.

[2] P. Jin, S. Fang, H. Lin, Z. Q. Zhu, Y. Huang, and X. Wang, "Analytical magnetic field analysis and prediction of cogging force and torque of a linear and rotary permanent magnet actuator," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 3004–3007, Oct. 2011.

[3] P. Bolognesi and F. Papini, "FEM modeling and analysis of a novel rotary-linear isotropic brushless machine," in *Proc. 19th ICEM Conf.*, Rome, Italy, Sep. 2010, pp. 1–6.

[4] M. Cheng, W. Hua, J. Zhang, and W. Zhao, "Overview of stator-permanent magnet brushless machines," *IEEE Trans. Ind. Electron.*, vol. 58, no. 11, pp. 5087–5101, Nov. 2011.

[5] 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, no. 2, pp. 806–815, Jun. 2015.

[6] J. H. Yan, H. Y. Lin, Y. Feng, and et al., "Cogging torque optimization of flux switching transverse flux permanent magnet machine," *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 2169-2172, 2013.

[7] Q. F. Lu, Y. X. Li, X. Y. Huang, and Y. Y. Ye. "Analysis of transverse flux linear switched flux permanent magnet machine," *IEEE Trans. Magn.*, vol. 51, no. 11, article# 8108804, 2015.

[8] M. Lin, L. Hao, X. Li, X. Zhao, and Z. Q. Zhu, "A novel axial field flux switching permanent magnet wind power generator," *IEEE Trans. Mag.,* vol. 47, no. 10, pp. 4457-4460, 2011.

[9] D. J. Evans and Z. Q. Zhu, "Novel partitioned stator switched flux permanent magnet machines," *IEEE Trans. Magn.*, vol. 51, no. 1, Jan. 2015, Art. no. 8100114.

[10] R. Cao, C. Mi, and M. Cheng, "Quantitative comparison of flux switching permanent-magnet motors with interior permanent magnet motor for EV, HEV, and PHEV applications," *IEEE Trans. Magn.*, vol. 48, no. 8, pp. 2374–2384, Dec. 2008.

[11] H. Weh, H. Hoffmann, and J. Landrath, "New permanent excited magnet synchronous machine with high efficiency at low speeds," in *Proc. Int. Conf. Electr*. Mach., vol. 3. Pisa, Italy, 1990, pp. 35–40

[12] Y. Ueda, H. Takahashi, A. Ogawa, T. Akiba, and M. Yoshida, "Cogging torque reduction of transverse-flux motor by skewing stator poles," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1–4, Jul. 2016.

[13] C. Liu, G. Lei, T. S. Wang, Y. G. Guo, Y. H. Wang, and J. G. Zhu, "Comparative study of small electrical machines with soft magnetic composite cores," *IEEE Trans. Ind. Electronics*, vol. 64, no. 2, pp. 1049-1060, 2017.

[14] Y. G. Guo, J. G. Zhu, P. A. Watterson, and W. Wu, "Development of a PM transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 426-434, June 2006.

[16] J. Doering, G. Steinborn and W. Hodman, "Torque, power, losses, and heat calculation of a transverse flux reluctance machine with soft magnetic composite materials and disk shaped rotor," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1494-1504, Mar./Apr. 2015

[17] J. Washington, J. Atkinson, and et al. "Three phase modulated pole machine topologies utilizing mutual flux paths," *IEEE Trans. Energy Conve.*, vol. 27, no. 2 pp: 507-515, 2012

[18] M. Keller, S. Muller, N. Parspour. "Design of a permanent magnet excited transverse flux machine for robotic applications" *XXII Int. conf. on elec. Mach.,* 2016, pp. 1520-1525

[19] C. Liu, G. Lei, B. Ma, Y. Wang, Y. Guo, and J. Zhu, "Development of a new low cost 3-D flux transverse flux FSPMM with soft magnetic composite cores and ferrite magnets," *IEEE Trans. Magn*., vol. 53, no. 11, , art. No. 8109805 May 2017.

Chengcheng Liu (S'14 – M'16) was born in Jiangsu, China in 1988. He received the B.E. degree in automation engineering from Yangzhou University, Yangzhou, China, in 2010 and the Ph.D. degree in electrical engineering from Hebei University of Technology, Tianjin, China, in 2016. He was a joint Ph.D. student supported by Chinese scholarship council in the University of Technology, Sydney, Australia.

He is currently a Lecturer of Hebei University of Technology, Tianjin China. His research interests include the design, analysis, control and optimization of electromagnetic devices.

Shaopeng Wang was born in Hebei, China, in 1993. He received the B.E. degree in Electrical Engineering from Hebei University of Technology, Tianjin, China, in 2016, where he is currently working toward the M.E. degree.

His current research interests include design and optimization of electromagnetic devices.

Youhua Wang received the B.E. degree from Xian Jiaotong University, Xian, China, in 1987; the M.E. degree from the Hebei University of Technology, Tianjin, China, in 1990; and the Ph.D. from Fuzhou University, Fuzhou, China, in 1994, all in electrical apparatus.

He is currently a Professor at the College of Electrical Engineering. His currently research interests include measurement and modeling of properties of magnetic materials, numerical analysis of the electromagnetic field, and electromagnetic device design, analysis and optimization.

Gang Lei (M'14) received the B.S. degree in mathematics from Huanggang Normal University, Huanggang, China, in 2003, and the M.S. degree in mathematics and the Ph.D. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2006 and 2009 respectively.

He is currently a Lecturer at the School

of Electrical and Data Engineering University of Technology Sydney, NSW, Australia. His current research interests include electromagnetic inverse problems, design optimization of electrical drive systems and renewable energy systems.

Youguang Guo (S'02 - M'05 – SM'06) received the B.E. degree from Huazhong University of Science and Technology, Wuhan, China, in 1985; the M.E. degree from the Zhejiang University, Zhejiang, China, in 1988; and the Ph.D. degree from the University of Technology, Sydney (UTS), NSW, Australia, in 2004, all in electrical engineering.

He is currently an Associate Professor at the School of Electrical and Data Engineering, University of Technology Sydney, UTS. His research fields include measurement and modeling of properties of magnetic materials, numerical analysis of the electromagnetic field, electrical machine design optimization, and power electronics drives and control.

Jianguo Zhu (S'90 – M'96 – SM'03) received the B.E. degree from Jiangsu Institute of Technology,Zhenjiang, China, in 1982; the M.E. degree from the Shanghai University of Technology, Shanghai, China, in 1987; and the Ph.D. degree from the University of Technology, Sydney (UTS), NSW, Australia, in 1995, all in electrical engineering.

He is currently a Professor of Electrical Engineering and the Head at the School of electrical and information engineering, University of Sydeny. His current research interests include electromagnetic, magnetic properties of materials, electrical machines, and drives, power electronics, and green energy systems.