New Laminated-Structure Flux Switching Permanent Magnet Machine for Plug-in Hybrid Electrical Vehicle with Novel Configuration

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Abstract — In this paper, a novel configuration for plug-in hybrid electric vehicle (PHEV) is introduced which has only one electric machine functioning as either a motor or generator at a time. For continuous working, more strict requirements are made to the drive machine, mainly including good thermal dissipation capability, high torque density, and great flux weakening ability. For the limitation of traditional machines, one new laminated-structure flux switching permanent magnet machine (LSFSPMM) is proposed. Different from the common FSPMM, the stator and rotor of LSFSPMM are laminated parallel to the axial direction, which can make full usage of PM flux linkage and reduce the iron loss particularly in the high excitation frequency. By the 2D model prediction of finite element algorithm, LSFSPMM has lower cogging torque, higher torque density, greater flux weakening ability and stronger thermal dissipation, hence it can be regarded as one ideal candidate for the proposed PHEV drive system. More experiments will be included in the full paper.

I. INTRODUCTION

There has been quick development of plug-in hybrid electrical vehicle (PHEV) in many countries due to the shortage of fossil fuels [1-2]. The electric drive system as one of key units in the PHEV plays important role for its widely successful commercialization. Fig. 1 shows a novel PHEV powertrain dependent on one electric machine was proposed in 2009 [2]. It consists of an energy storage unit comprising of batteries and super-capacitors, a power control unit including the DC link, DC/DC converters and a back to back inverter/rectifier, an electric machine, MG, functioning as either a motor or a generator, and an ICE working mainly during fast acceleration to provide the extra torque required. The system operation is governed by a special energy management strategy [2]. However, the new configuration has more strict requirements for the drive machine, i.e. higher torque/power density, flux-weakening ability for wider high-speed cruising range, thermal dissipation ability for continuous working, stronger mechanical robustness, excellent efficiency, terrific overload capability, and so on.

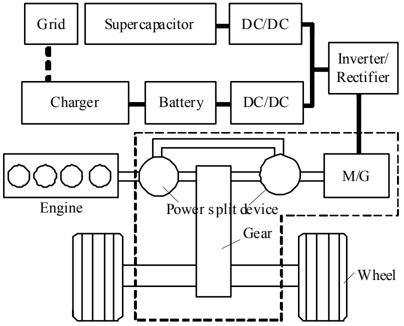


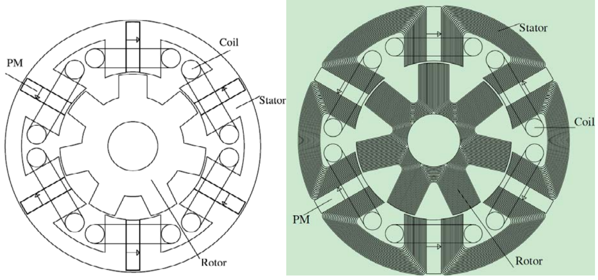
Fig.1. Proposed PHEV configuration.

II. NEW LAMINATED STRUCTURE FSPMM

By many researchers' hard work during the past decades, the flux-switching permanent magnet machine (FSPMM), as shown in Fig.2 (a), has come into notice of automobile companies. It is a doubly-salient PM brushless machine, having both windings and magnets in the stator. The rotor is only a salient passive rotor with great mechanical robustness. For inheriting the merits of both switched reluctance machine and traditional rotor-PM machine, it has good attributes of high torque/power density, high efficiency, excellent flux-weakening capability, stronge robustness, and convenience of cooling.

However, the FSPMM has serious partial magnetic saturation for its nonlinear magnetic path, which maximal flux density is usually more than 2.8 T occurring at the edges of stator or rotor poles. Moreover, the number of pole pairs equal to the number of rotor pole is comparatively larger, hence its rated frequency of stator current is higher at one given speed, e.g. it could reach 175 Hz @ 1500 rpm in the structure of 6/7 poles. In this case, the iron and eddy losses especially beyond the rated speed are very evident so to decrease the machine efficiency.

In order to smooth away the aforementioned problems, one new laminated-structure FSPMM (LS-FSPMM) as illustrated in Fig. 2(b) is proposed. Different from the traditional FSPMM laminated vertical to the axial direction, the new structure is laminated parallel along the axis. As seen from Fig. 2(b), the stator includes 6 respective laminated modules, while the rotor involves 7 modules, all are made of 0.3 mm high grain oriented silicon steel sheet (HIB). The flux linkage loops along each laminated steel, which makes full usage of PM, and decreases hysteresis and eddy losses both in the stator and rotor.

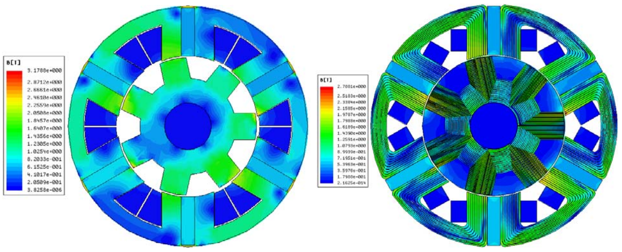


(a) Traditional structure. (b) New laminated structure.

Fig.2. FSPMMs with 6/7 poles.

III. PERFORMANCE ANALYSIS

The traditional and new structure FSPMMs are designed in the same dimensions: active length of 49 mm, shaft radius 10.6 mm, outer rotor radius 31.4mm, air gap length 0.6 mm, inner stator radius 32mm, outer stator radius 54.6 mm, width of PM 6 mm, and number of winding per phase in series 78. By the prediction of 2D model analyzed by finite element algorithm (FEA), the partial magnetic saturation of the new structure compared with the conventional one is lower for its more effective usage of PM benefited from the laminated structure, as indicated in Fig. 3. Some typical performance curves including flux linkage, back EMF, cogging torque, and rated torque, are shown in Figs. 4-7 respectively. It is evident to see that the new structure has lower cogging torque, and higher flux linkage, back EMF and rated torque under the same excitation.



(a) Traditional structure. (b) New laminated structure.

Fig.3. Flux density nephogram in FSPMMs with 6/7 poles.

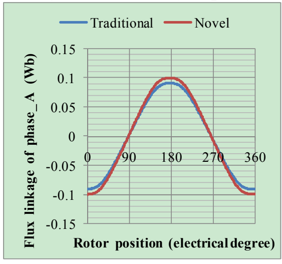


Fig.4. Flux linkage of Phase_A.

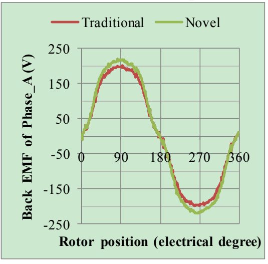


Fig.5. Back EMF of Phase_A.

Great flux weakening ability is very important to the PHEV drive system because it can enlarge the high speed cruising region, which is defined as,

$$\beta = \frac{\psi_m}{\psi_m - \psi_d} = \frac{\psi_m}{\psi_m - L_d i_d} \qquad (1)$$

where Ψ_m is permanent magnet flux linkage, L_d the equivalent d-axis inductance, i_d the d-axis current. By employing the new lamination, the L_d becomes larger so to increase β from 4 in the traditional machine to 4.67 in the new machine.

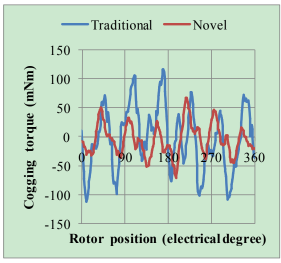


Fig.6. Cogging torque.

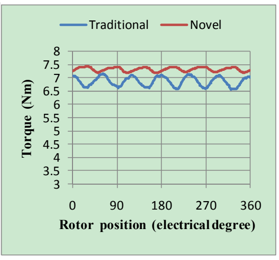


Fig.7. Rated torque@1500rpm.

The efficiency should be taken careful consideration in the design stage, which is calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_f + P_c + P_i} \qquad (2)$$

where P_{out} is output active power, P_f friction power loss, P_c copper loss, and P_i iron loss. Based on the data provided by the manufacturer, P_i under time-varying flux is separated into a hysteresis loss component P_h and an eddy current loss component P_c, both in W/kg as indicated by

$$P_i = P_h + P_e = k_h f^2 B_m^\alpha + k_e f^2 B_m^2 \quad (3)$$

where f and B are the frequency and the peak value of the magnetic flux density, respectively; k_h, k_e and α are the loss coefficients of the material provided by the manufacturer.

The curves of torque and efficiency in different speed are given in Figs. 8 and 9. For great reduction of iron loss in the new lamination, it has higher torque and efficiency particularly beyond the base speed.

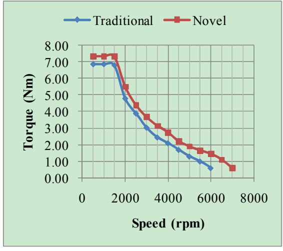


Fig.8. Torque in the different speed.

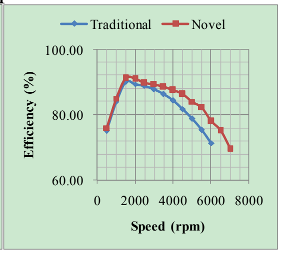
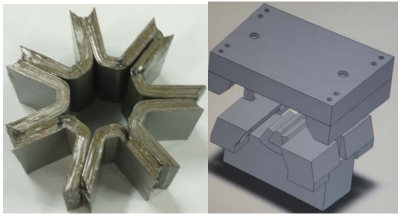


Fig.9. Efficiency in different speed.

IV. PROTOTYPE FABRICATION

The LS-FSPMM is being built up in the mechanical worshp in University of Technology Sydney. Fig. 10 shows the real rotor and the stator module in design. All the modules will be finished in one month, and then experiments will be compared with the simulation.



(a) Real rotor. (b) Designed stator.

Fig.10. FSPMM with 6/7 poles in fabrication.

V. CONCLUSIONS

One new LSFSPMM for the proposed PHEV configuration is set up and analyzed by the FEA 2D model in this paper. Compared with the conventional FSPMM, it has smaller partial magnetic saturation at edges of stator and rotor teeth for its axial lamination consisting of HIB. For its radial magnetic resistance, it can reduce the iron loss greatly especially in the region of high excitation frequency. The simulation indicates it has lower cogging torque, stronger flux weakening ability and higher torque. Testing data will be available in the full paper.

VI. REFERENCES

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

[2] W. Xu, J.G. Zhu, *et al.*, "Drive system analysis of a novel plug-in hybrid vehicle," in *Proc. IEEE Industrial Electronics Society*, Nov. 2009, pp. 3717 - 3722.