

# Loss and efficiency of a flux-switching permanent-magnet double-rotor machine with high torque density

Lihong Mo<sup>1</sup>, Xiaoyong Zhu<sup>2</sup>, Li Quan<sup>2</sup>, Tao Zhang<sup>1</sup>, Juan Huang<sup>2</sup>, Xue Wang<sup>2</sup>

<sup>1</sup> Faculty of Automation, Huaiyin Institute of Technology, Huai'an, CO 223003 China, [xueren502@163.com](mailto:xueren502@163.com)

<sup>2</sup> School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, CO 212013 China, [xueren502@163.com](mailto:xueren502@163.com)

The flux switching permanent magnet double rotor machine (FSPM-DRM) used for hybrid electric vehicles (HEVs) has attracted considerable attention due to the compact structure and high torque density. Compared with conventional machine, the FSPM-DRM suffers from more iron loss, PM eddy current loss and conductor eddy current loss for its larger rotor pole numbers. The iron loss exists not only in the stator but also in the rotor, while its calculation becomes more difficult due to complex flux density waveforms. A more accurate analytical model for the iron loss, PM eddy current loss and conductor eddy current loss calculation is proposed for the FSPM-DRM machine and compared with results from FEM, with due consideration of the influence of operation conditions, including constant torque and flux-weakening. Based on the calculated losses, the efficiency of the FSPM-DRM is also investigated. Some experimental results are reported, validating the numerical and simulated results.

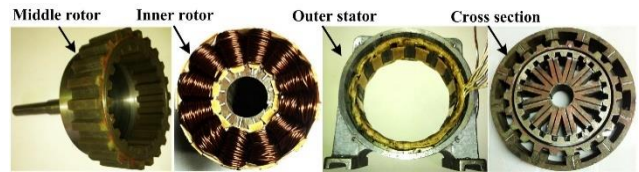
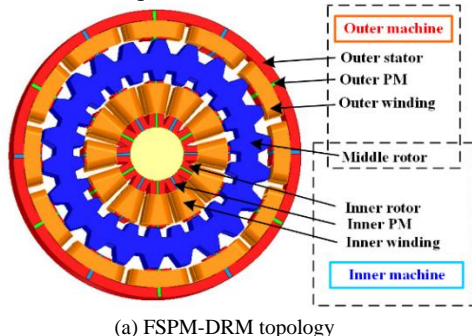
**Index Terms**—Flux switching permanent magnet machine, double-rotor machine, loss, efficiency, finite element method

## I. INTRODUCTION

Double rotor machine (DRM) used for hybrid electric vehicles (HEVs) can offer multi-operational modes and enables the internal combustion engine (ICE) to operate at optimum efficiency independent of road conditions, thus decreasing the emissions and fuel consumption. To achieve high torque density and little torque ripple, recently, a flux-switching permanent-magnet double-rotor machine (FSPM-DRM) has been proposed (see Fig. 1(a)) [1][2]. Besides the high torque density, the FSPM-DRM used for HEV should has high efficiency at different operation mode during wide speed range. So, to verify the machine's performance, it's essential to investigated the FSPM-DRM loss and efficiency accurately, which is also needed for further thermal analysis.

## II. MACHINE TOPOLOGY

Fig.1 shows the configuration of the FSPM-DR machine, in which two 12/22-pole and three-phase FSPM machines are artfully integrated and thus a compact structure and lower torque ripple can be obtained. It has three basic parts: an outer stator, a middle rotor and an inner rotor. Three parts are separated by two air gaps but coupled magnetically. The proposed FSPM-DR machine can be regarded as an integration of the two machines, namely, the outer machine which are composed of the outer stator and the middle rotor, and the inner machine which are composed of the inner rotor and middle rotor.

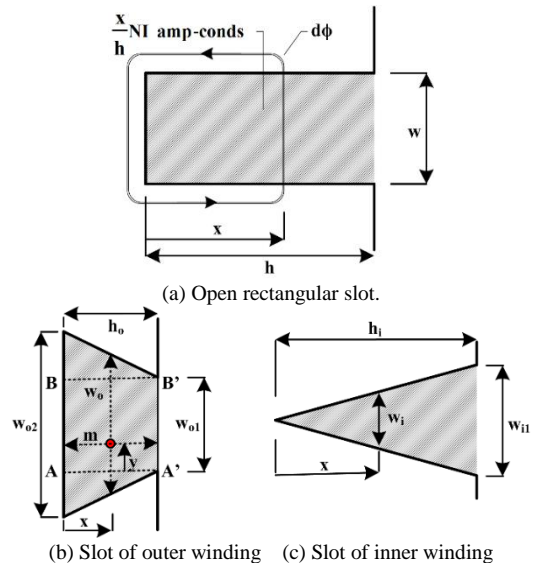


(b) Prototype photo  
Fig.1. FSPM-DRM topology and prototype photo.

## III. LOSS ANALYSIS

### A. Eddy current loss in windings

In the FSPM-DRM, the proximity loss dominates skin effect loss because that in its double-layer windings the total magnetic field is much larger than the field generated only by one strand or turn, and that the conductor diameters of the inner and the outer machines are smaller (1.4mm and 1.18mm) than the skin depth at the 7 times of rated speed (1.51mm). So, in the following analysis the skin effect is negligible.



(b) Slot of outer winding (c) Slot of inner winding  
Fig.2. Schematic of slot areas.

The proximity loss  $P_c$  within a conductor in the presence of a time-varying ac magnetic field with a peak value of  $B_m$  can be modelled as:

$$P_e = \frac{\pi d^4 \omega^2 B_m^2 l}{128 \rho_c} \quad (1)$$

$$B = \mu_0 H = \frac{\mu_0 x}{w} NI \quad (2)$$

where  $d$  and  $l$  are the diameter and the length of a conductor.  $\rho_c$  is the resistivity of copper.  $B_m$  and  $\omega$  are the peak value and the angular velocity of flux density harmonic.  $B$  is the cross-slot flux density considering the variation of the flux density of a conductor with its depth  $x$  in the slot for regular rectangular slot, (Fig.2(a)).  $\mu_0$  is the permeability of free air space.  $x$  is the depth in the slot for calculating the slot leakage.  $w$  and  $h$  are the width and the depth of the slot, separately.

While, the slots of the outer stator and the inner rotor in the FSPM-DRM are nearly trapezoid and triangular shapes, which does not match the assumed rectangular shape, as is shown in Fig.3(b) and Fig.3(c). To make the analysis more accurate, some transformations are needed. Take the outer slot as an example, the relatively large width  $y$  compared with the its depth  $x$ , the variation of the flux density with tangential direction should be also considered. Based on the rules of ampere-turns changing with area, (3) is the flux density in the outer slot adopting improved scheme.

$$B_{outxy} = \begin{cases} \frac{\mu_0 (w_{o2} - w_{o1} - 4|y|)^2}{m (w_{o2} - w_{o1})^2} N_o I_o & y \in [-(\frac{w_o}{2} - \frac{w_{o1}}{2}), 0] \\ \frac{\mu_0 w_{o2} - w_{o1} + 8y}{h_o w_{o2} - w_{o1}} N_o I_o & y \in (0, \frac{w_{o1}}{2}] \end{cases}$$

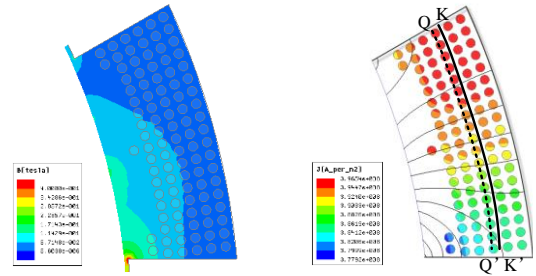
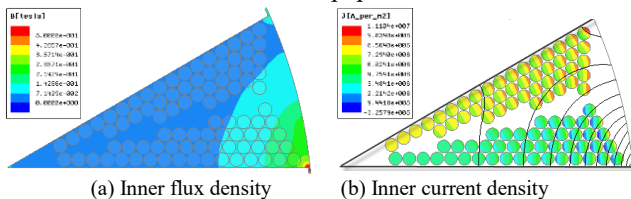
$$= \begin{cases} \frac{w_{o2} - w_{o1} - 4|y|}{2(w_{o2} - w_{o1})} B_{outx} & y \in [-(\frac{w_o}{2} - \frac{w_{o1}}{2}), 0] \\ \frac{w_{o2} - w_{o1} + 8y}{2(w_{o2} - w_{o1})} B_{outx} & y \in (0, \frac{w_{o1}}{2}] \end{cases}$$

$$m = \begin{cases} \frac{h_o (w_{o2} - w_{o1} - 4|y|)}{w_{o2} - w_{o1}} & y \in [-(\frac{w_o}{2} - \frac{w_{o1}}{2}), 0] \\ h_o & y \in (0, \frac{w_{o1}}{2}] \end{cases}$$

where  $h_o$ ,  $w_{o1}$ , and  $w_{o2}$  are defined in Fig.2(b).  $w_o$  is the slot width at the given slot depth  $x$  in the outer slot.

### B. FEA method

The current distributions of the inner and the outer slots at certain rotor position are also shown in Fig.3. The conductors closest to slot opening and near the tangential center region of the outer slot experience the highest induced eddy current loss, which is helpful for conductor's placement design. The core loss and PM eddy current loss at different current and operation mode will be discussed in detail paper.



(c) Outer flux density (d) Outer current density  
Fig. 3. Simulated flux density and current density distributions

## IV. EFFICIENCY

Table I and Table II list the FSPM-DRM's loss and efficiencies at various operation conditions. The inner and the outer machines of the FSPM-DRM exhibit excellent efficiencies in different operation areas, which is favorable for HEV applications [3][4].

Table I The losses and efficiencies at rated load

Parameters	Inner	Outer
DC copper loss ( W )	48.4	50.9
Eddy current loss in windings(W )	13.1	10.6
Iron loss ( W )	24.2	23.7
Eddy current loss in PM ( W )	12.9	4.4
Output torque ( N.m )	14.3	12.3
Power ( W )	1123	966
Efficiency ( % )	91.9	91.5

Table II The efficiencies of inner and outer machines at different speed

Speed(rpm)	500	750	1500	2000
Inner efficiency(%)	89.5	91.9	92.2	91.6
Outer efficiency(%)	91.1	91.5	93.2	91.8

## V. VALIDATION AND CONCLUSION

A prototype machine of the FSPM-DRM was designed and manufactured for the testing facilities and concept validation (Fig.1(b)). From the comparisons of the results from improved analytical calculation, FEA simulation and experimental verification, we can see the similarities of two topologies' electromagnetic performances, as well as, the differences, which is helpful for machine design and performance optimization..

## REFERENCES

- [1] Lihong Mo, li Quan, Xiaoyong Zhu, "Comparison and analysis of flux-switching permanent-magnet double-rotor machine with 4QT used for HEV," IEEE Transaction on Magnetics, Vol. 50, No.11, 2014, Art. ID 8205804.
- [2] Chen Yunyun, Quan Li, Zhu Xiaoyong, Wei Hua, and Zheng Wang, "Electromagnetic Performance Analysis of Double-Rotor Stator Permanent Magnet Motor for Hybrid Electric Vehicle," IEEE Transactions on Magnetics, vol. 48, no. 11, pp. 4204-4207, 2012.
- [3] Ruiwu Cao, Chris Mi, and Ming Cheng, "Quantitative Comparison of Flux-Switching Permanent-Magnet Motors With Interior Permanent Magnet Motor for EV, HEV, and PHEV Applications," IEEE Transactions on Magnetics, vol. 48, no. 8, pp.2374-2384, 2012.
- [4] Zixuan Xiang, Li Quan, Xiaoyong Zhu, "A new partitioned-rotor flux-switching permanent magnet motor with high torque density and improved magnet utilization," IEEE Transaction on Applied Superconductivity, Vol.26, No.4, 2016, Art. ID 5201905.