# Reduction of Eddy-Current Losses by Circumferential and Radial PM Segmentation in Axial Flux Permanent Magnet Machines with Fractional-Slot Winding

Jian Li[1], Yun-Hyun Cho[2] and Ronghai Qu[1], *Senior Member, IEEE*
[1]State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, 430074, China
[2]Dept. of Electrical Engineering, Dong-A University, Busan, 604714, South Korea

**Abstract—This paper studies the eddy current losses of axial flux PM machines with circumferential and radial PM segmentation. The fractional-slot concentrated winding has large amount of magneto-motive force (MMF) harmonics, which increases eddy-current losses in magnets and rotor yoke, especially the space harmonics contains sub order component. Proper segmentation of permanent magnets was introduced to reduce eddy current losses. In this paper, a finite element model was utilized to study the eddy current loss generation according to the different slot/pole combinations with circumferential segmentation. After number of circumferential segmentation was optimized, PM segments in radial direction was studied by 3 dimensional finite element analysis.**

## I. Introduction

Eddy current losses is an typical problem in permanent magnet machines especially with machine equipped with fractional-slot concentrated windings. PM segmentation in radial flux PM machines have been widely studied in literature. Both circumferential and axial magnet segmentations were evaluated by an analytical method concerning the skin effect in [1], and it was pointed that PM segmentation may increase rather than reduce the eddy current losses when skin depth is small than pole-arc width and radial height". Analytical calculation of eddy current loss due to space harmonics has been given in [2-4] to investigate the effect of circumferential or axial PM segmentation for loss reduction. The reported analytical methods to calculate eddy current losses were validated by 2-D time-stepping finite element (FE) analysis [2, 3] and by 3-D magneto-static FE analysis[4], for cases when skin depth at the frequency of interest is greater than both pole-arc and radial dimensions of magnets. Axial flux permanent magnet machines have various merits over radial flux machines, such as high torque density, short axial length and compact construction, thus they are proposed for wind turbines [5], electric vehicles [6] and ships [7]. Eddy current loss problem in concentrated winding axial flux PM machine with plastic bonded magnets and sintered segmented magnets was studied at not load, load and un-magnetized conditions in [8].

In cases of axial flux PM machines, PM segmentation could be achieved by circumferential and radial PM segmentation. The fractional-slot concentrated winding has large amount of magneto-motive force (MMF) harmonics, which increases eddy-current losses in magnets and rotor yoke, especially the sub-harmonic component. In this paper, a 2-D finite element model was utilized to study circumferential segmentation according to different slot/pole combinations. After number of circumferential segmentation was optimized, PM segments in radial direction was studied by 3 dimensional finite element analysis.

## II. Analysis and Results

### A. Circumferential Segmentation

The MMF distribution is represented by its harmonic components, using the Fourier series expansion. Then, for each $v$-th MMF harmonic, the following procedure is adopted:

- The stator is substituted by an infinitesimal conductive sheet placed at the stator inner diameter $D_{si}$.

- A liner current density $K_{sv}(\theta)$, sinusoidally distributed in the space, is imposed in such a conductive sheet. The distribution is described by $\sin(v\theta)$, where $\theta$ is in mechanical radians. The peak value of linear current density is obtained from the corresponding amplitude of the MMF harmonic $\hat{U}_{sv}$ as

$$\hat{K}_{sv} = \frac{2v\hat{U}_{sv}}{D_{si}} \tag{1}$$

- The circumference is split in a large number of points, $N_p$. Their distance is $\pi D_{si}/N_p$. In each point a prefixed point current $I_{pv}$ is assigned, as shown in Fig.1. According to the $v$-th harmonic, the maximum current value is computed from the electric loading $\hat{K}_{sv}$, as $\hat{I}_{sv} = \hat{K}_{sv}\pi D_{si}/N_p$.

- The linear current density waveform rotates along the air-gap with a fixed speed $\omega_{rv}$ as given by Equation in the rotor reference frame. Thus the source current has to be alternating at a frequency given by Equation Using the symbolic notation, in the generic angular position $\theta$, the point current is forced to be

$$\dot{I}_{pv}(\theta) = \hat{I}_{pv}e^{jv\theta} \tag{2}$$

The phase of current is fixed to be a function of the geometrical position $\theta$ of the point in which the point current is assigned.Three models of a double-layered 72slots 64 poles machine are computed using finite element method. The MMF amplitude, peak electric loading( $\hat{K}_{sv}$) and rotor induced frequency ($f_{rv}$) as given in Fig. 2. These three models have same stators but different rotor structures:

1) Model 1 is a simplified mode which has the permanent magnet as a single conductive sheet;

2) Model 2 is has a rotor with $\alpha_p = 0.8$, and no segment in PMs;

3) Model 3 has the PMs segmented in circumferential direction.

The rotor losses are split according the losses associated to each harmonic order given in Fig.2, from which it could be found that the highest rotor loss is generated at harmonic order of $\upsilon = 40$. This harmonic order has same linear current density as main harmonic order of $\upsilon = p = 32$. The rotor loss at this order may be effectively reduced by segmentation of PMs in circumferential direction as show in Fig.2 (c). And the corresponding eddy-current density distributions are illustrated in Fig. 3. After superposition, the total are losses are 1260W, 948W and 253W, respectively.

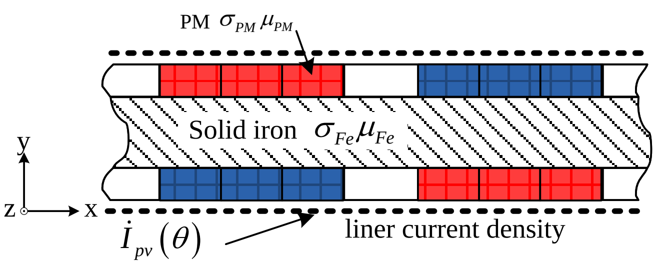



Fig. 1 Model used for FE computation

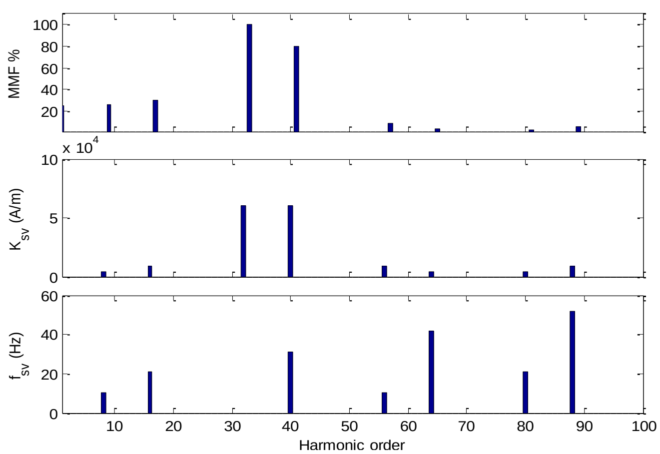
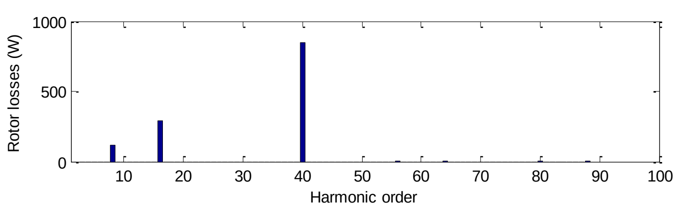
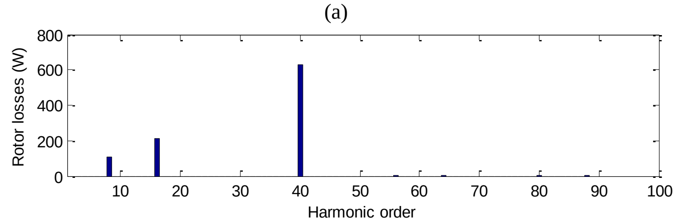


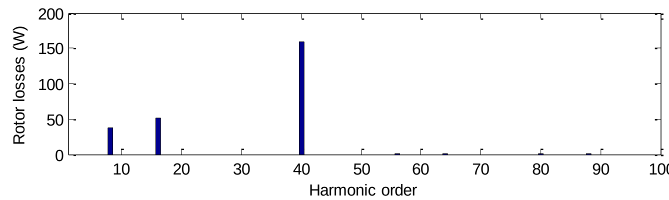

Fig. 2. Double-layer winding with 72 slots and 64 poles: MMF amplitude (%), peak electric loading$(\hat{K}_{sv})$ and rotor induced frequency $(f_{rv})$.




(a)




(b)




(c)

Fig. 3. Rotor losses of three models, (a) model 1, (b) model 2 and (c) model 3.

## *B Radial Segmentation*

Radial PM segmentation was analyzed by transient 3-D finite element method. The model which contains 16 PM segments in radial direction and rotor yoke was given in Fig. 4. And the vector plot of eddy current was illustrated in Fig. 5. More results of segmentation would be summarized and further discussions would be given in full paper.

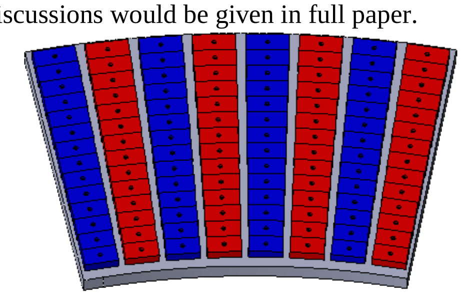


Fig. 4. Model of radial Segmentation

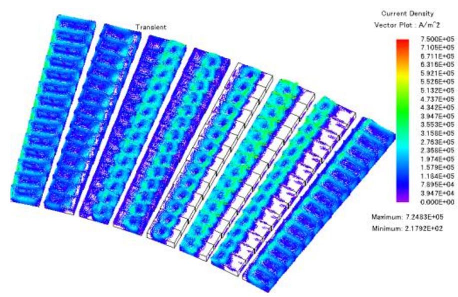



Fig. 5. Vector plot of eddy current in PMs at full load

## III. References


[1] W. Y. Huang, *et al.*, "Optimization of Magnet Segmentation for Reduction of Eddy-Current Losses in Permanent Magnet Synchronous Machine," *IEEE Transactions on Energy Conversion,* vol. 25, pp. 381-387, Jun 2010.

[2] H. Toda, *et al.*, "Rotor eddy-current loss in permanent magnet brushless machines," *IEEE Transactions on Magnetics,* vol. 40, pp. 2104-2106, Jul 2004.

[3] K. Altallah, "Rotor loss in Permanent-magnet brushless AC machines," *IEEE Trans. Ind. Appl.*, vol. 36, pp. 1612-1617, Nov. 2000.

[4] J. D. Ede et al., "Effect of Axial segmentation of permanent magnets on rotor loss in modular permanent-magnet brushless machines," *IEEE Trans. Ind. Appl.*, vol. 43, pp. 1207–1213, Sep. 2007.

[5] T. F. Chan and L. L. Lai, "An axial-flux permanent-magnet synchronous generator for a direct-coupled wind-turbine system," *Ieee Transactions on Energy Conversion,* vol. 22, pp. 86-94, Mar 2007.

[6] F. Crescimbini, *et al.*, "Compact permanent-magnet generator for hybrid vehicle applications," in *Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the*, 2003, pp. 576-583 vol.1.

[7] F. C. F. Caricchi, and O. Honorati, "Modular axial-flux permanent magnet motor for ship propulsion drives," *IEEE Trans. on Energy Conversion,* vol. 14, pp. 673-679, 1999.

[8] H. Jussila, *et al.*, "Concentrated winding axial flux permanent magnet motor with plastic bonded magnets and sintered segmented magnets," in *Electrical Machines, 2008. ICEM 2008. 18th International Conference on*, 2008, pp. 1-5.