Compumag 2011

12 - 15 July 2011, Sydney, Australia

18th International Conference on the Computation of Electromagnetic Fields

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TECHNICAL PROGRAM

(Draft on 22 June 2011)

Session PD5: Electric Machines and Drives (X)

11:30-12:45 – Bayside Gallery

PD5.1 (ID 783)
Analysis and Design of Slotted Tubular Linear Actuator for the Eco-Pedal System of a Vehicle
Kim, Young Kyoun (1); Gu, Bon-Gwan (1); Jung, In-Soung (1); Won, Sung-Hong (2)
1: Korea Electronics Technology Institute, Korea, South (Republic of); 2: Dept. of Electric System, Dongyang Mirae University, Korea, South (Republic of)

PD5.2 (ID 785)
Full and Simplified Loss Calculation FEM Models for Segmented Surface Permanent Magnet Machines
Funieru, Bogdan; Mirzaei, Mehran; Binder, Andreas
TU Darmstadt, Germany

PD5.3 (ID 786)
Optimal Design of Line-Start Permanent Magnet Motor with Cost Reduction and Performance Improvements
Li, Jian; Song, Jeong-Tae; Cho, Yun-Hyun
Dong-A University, Korea, South (Republic of)

PD5.4 (ID 802)
Analysis and Modeling of Stator Slot-Opening Effect on Open-Circuit Air-gap Field Distribution in Interior-type Permanent Magnet Machine
Fang, Liang; Kim, Do Jin; Hong, Jung-pyo
Hanyang University, Korea, South (Republic of)

PD5.5 (ID 826)
Diagnosis of Phase to Phase Short Circuit Faults in Vector Controlled Permanent Magnet Synchronous Motors
Djerdir, Abdesslem (1); Hadef, Mounir (1,2); Mekideche, Mohamed (2); N'diaye, Abdoul-Osmane (1); Miraoui, Abdellatif (1)
1: SET/UTBM, France; 2: Université de Jijel/LAMEL, Algérie

PD5.6 (ID 839)
The Reduction of Torque Ripple in Spoke type Transverse Flux Rotary Machine for Direct Drive Motor
Hong, Do-Kwan; Lee, Ji-Young; Woo, Byung-Chul; Chung, Si-Uk
Korea Electrotechnology Research Institute, Korea, South (Republic of)

PD5.7 (ID 844)
An Analytical and Numerical Model to Predict Static and Dynamic Performance of a Torus Machine with Two Permanent Magnets Topologies
Martins Osório, Jonas Obert; Ferreira Flores Filho, Aly; Eckert, Paulo Roberto; Tiaraju dos Reis Loureiro, Luiz
Federal University of Rio Grande do Sul, Brazil

PD5.8 (ID 845)
Modeling and Analysis of Synchronous Machines with Broken Damper Bars
Rahimian, Mina
Texas A&M University, United States of America

Analysis and Modeling of Stator Slot-opening Effect on Open-circuit Air-gap Field Distribution in Interior Permanent Magnet Machine

Liang Fang, Do-Jin Kim, Hae-Joong Kim, Jung-Pyo Hong, *Senior, IEEE*

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This paper proposes an effective analytical modeling for considering the stator slot-opening effect on air-gap field distribution in an interior permanent magnet (IPM) machine. Unlike the simple surface PM (SPM) machine situation, an additional effect of slot-opening uniquely exists in IPM machine, that the magnet pole flux distortion in the IPM rotor core increases the air-gap flux density. This analytical modeling is built for precisely considering the flux concentration. The assistant modeling coupled with basic analytical model of IPM motor is then applied to analyze the air gap field distribution, and its validity is well confirmed by finite element method.

***Index Terms*—Analytical method, assistant models, effective pole-arc, finite element method, SPM/IPM machine**

I. Introduction

Due to high efficiency, high power density, and high torque density, together with the development of permanent magnet (PM) material and power electronics, the PM brushless machines are increasingly being used in various applications, such as variable-speed drives, servo drives, electric vehicles, and other industrial drives [1].

Compared with surface-mounted PM (SPM) machines, interior-type PM (IPM) machines have superior advantages on robust rotor construction and high reluctance torque due to the unique rotor structure that PMs buried inside rotor core [2]. However, the complex rotor structure increases the difficulty and time-consuming in IPM machine designs.

From the previous work [3], [4], a well-accepted analytical model of typical SPM machine is built with consideration of slot-opening effect on the air-gap flux density distribution, in APPENDIX. Under an assumed field pattern between rotor and stator surfaces, the flux crosses the magnet and air-gap in a straight line, wherever a magnet faces a tooth and in a circular path, centred about the corner of a tooth, wherever a magnet faces a slot opening [3], the slot-opening effect is well considered by using relative permeance method [3], [4].

Unlike the SPM motor structure, whose flux source (PM) closing to stator surface, the IPM motor inserts PMs into the rotor core, away from stator surface. This unique structure results in the flux pass through the high permeance rotor iron core before crossing out of rotor surface into air-gap, which results in the magnet flux concentrating on forward to the stator teeth regions, while avoiding to face to slot-opening regions. That is, the slot-opening has multiple effect on air-gap region and IPM rotor core, therefore the relative permeance method used for dealing with common slot-opening effect in SPM situation is not worked for IPM machine analysis. For considering this unique slot-opening effect phenomenon, an assistant analytical model is proposed in this paper, which helps to analytically predict the air-gap field distribution preciously. The validity of proposed analytical model is verified by comparing the analytical results with FEM solution.

Manuscript received December 15, 2010.
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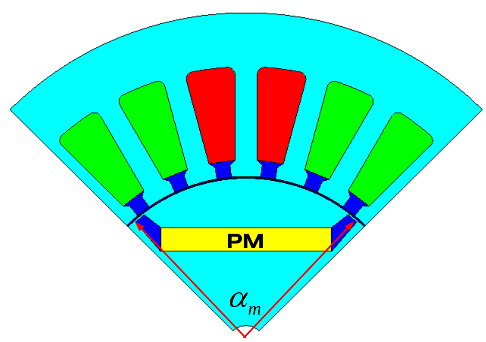
II. Models and Methods

Analysis Model of an IPM Motor

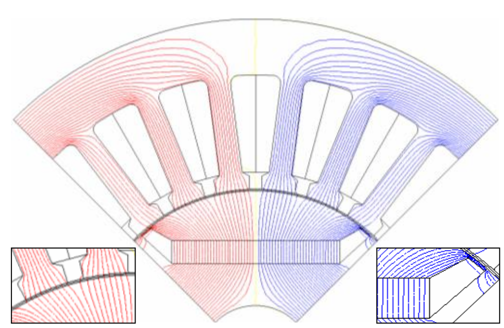
In this paper, a conventional 4-pole/24-slot ($p=4$, $Q_s=24$) IPM motor (IPMM) with radial magnetization is built as an analysis model based on another SPM motor (SPMM) model, given in APPENDIX. These two models have identical machine dimensions, and use the same materials in analysis.

Unique Magnetic Field in IPM Motor

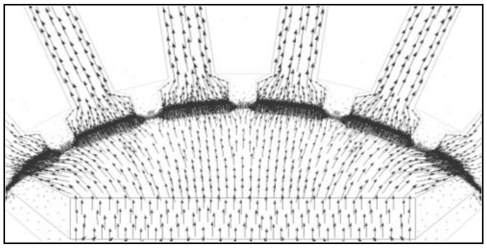
By performing FEM in the given IPMM model, the high saturated rib regions and flux distortion inside the IPM rotor core caused by the unique IPM rotor structure with slot-opening effect can be found as shown in Fig. 1. Especially in Fig. 1(c), the magnet pole flux concentrates on forward to the teeth regions, while avoids to face to slot-opening regions before crossing rotor surface into air gap is clearly observed.



(a). Analysis model of a conventional IPM motor



(b). Emphasized flux path distortion (left) and saturated rib region (right)



(c). Magnet pole flux distortion phenomenon in IPM rotor core

Fig. 1 Open-circuit analysis of magnetic field in IPMM model by FEM

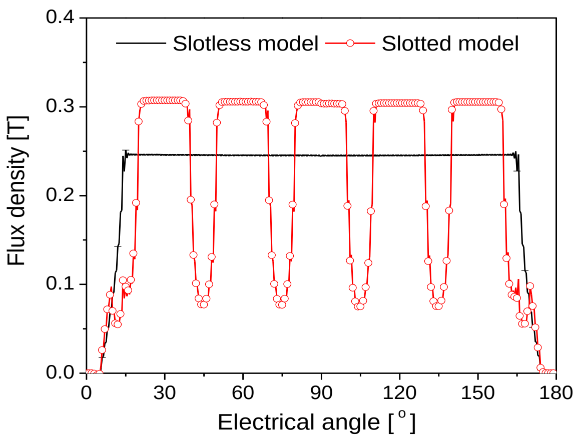


Fig. 2 Comparison of air gap flux density in slotless/slotted IPMM by FEM

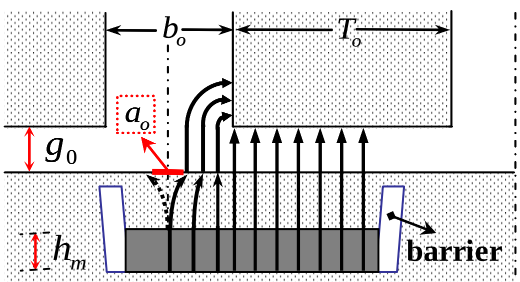
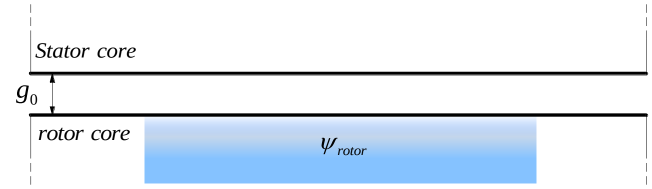


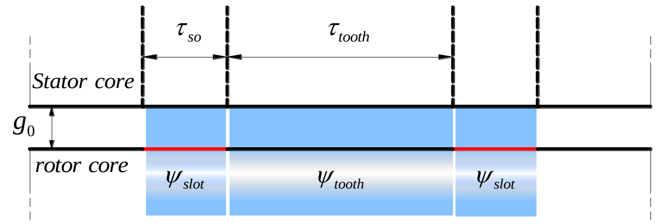
Fig. 2 Assumed flux distortion pattern for considering effective pole arc

The magnet flux distortion due to slot-opening effect in IPM rotor core results in an increase of air gap flux density, as proved by FEM in Fig. 2. This flux distortion effect is described by a simplified model, as Fig. 3 shows, that the "α_0" region has quite little flux crossing out to the slot-opening region, which also means that the effectiveness of "α_0" regions as magnetic pole-arc "τ_{pole}" is lower. And, the visual air gap flux density under the teeth region will be enhanced because of the equivalently decreased magnetic pole-arc "τ_{pole}".

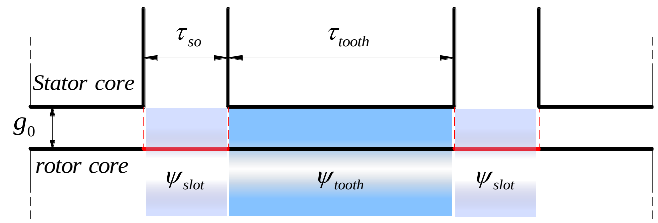
In this paper, an assistant model is built for analytically considering the flux distortion effect on the air gap field in the IPM rotor, as Fig. 4 shows. The assistant model is built according to the magnet pole flux distribution in slotless and slotted models, respectively. In model (a) and (b), the total magnet flux ψ_{rotor} of one PM pole is divided into ψ_{slot} part and ψ_{tooth} part. Then, the decreased flux of ψ'_{slot} is compensated to the ψ'_{tooth} part according to the comparison of tooth part ($\psi'_{tooth}/\psi_{tooth}$) in slotted IPMM model. In model (c), the low flux density at slot-opening regions is dealt with by improving the relative permeance calculated by using conformal mapping method [5], for considering the flux distortion, as Fig. 5 shows.



(a) IPM flux crossing rotor core into air gap in slotless model



(b) Assumed IPM flux separately crossing into air gap in slotless model



(c) Assumed IPM rotor flux separately crossing into air gap in slotted model

Fig. 4 Assitant models for considering flux distortion effect in IPM motor.

(1). Magnet pole flux distribution in slotless model:

$$\psi_{rotor} = B_{g-slotless} \cdot \left(\tau_p \cdot R_{rotor}\right) \cdot L_{stake} = \sum_{\tau_p} \psi_{slot} + \sum_{\tau_p} \psi_{tooth} \tag{1}$$

$$B_{g-slotless} = \frac{\psi_{slot}}{\left(\tau_{so} \cdot R_{rotor}\right) \cdot L_{stake}} \tag{2}$$

$$B_{g-slotless} = \frac{\psi_{tooth}}{\left(\tau_t \cdot R_{rotor}\right) \cdot L_{stake}} \tag{3}$$

$$\psi_{tooth} = \psi_{rotor} - \left[\alpha_{p\_(pole-arc/pole-pitch)} \cdot Q_s / p\right] \cdot \psi_{slot} \tag{4}$$

(2). Flux distortion due to slot-opening effect:

$$\hat{\lambda}'_{slot} = \frac{1}{\tau_{so}} \sum_{\tau_{so}} \hat{\lambda}_{slot}\left(\theta\right) \tag{5}$$

$$\psi'_{slot} = \psi_{slot} \cdot \hat{\lambda}'_{slot} \tag{6}$$

$$\sum_{\tau_p} \psi'_{slot} = \left(\alpha_p \cdot Q_s / p\right) \cdot \psi'_{slot} = \left(\alpha_p \cdot Q_s / p\right) \cdot \psi_{slot} \cdot \hat{\lambda}'_{slot} \tag{7}$$

$$\psi'_{tooth} = \psi_{rotor} - \sum_{\tau_p} \psi'_{slot} = \psi_{rotor} - \left(\alpha_p \cdot Q_s / p\right) \cdot \psi_{slot} \cdot \hat{\lambda}'_{slot} \tag{8}$$

(3). Coefficient factor of magnet flux concentration:

$$\kappa_{slot} = \frac{\psi'_{tooth}}{\psi_{tooth}} = \frac{\psi_{rotor} - \left(\alpha_p \cdot Q_s / p\right) \cdot \psi_{slot} \cdot \hat{\lambda}'_{slot}}{\psi_{rotor} - \left(\alpha_p \cdot Q_s / p\right) \cdot \psi_{slot}} = \frac{\pi - \left(Q_s / p\right) \cdot \tau_{so} \cdot \hat{\lambda}'_{slot}}{\pi - \left(Q_s / p\right) \cdot \tau_{so}} \tag{9}$$

$$B_{g-slotless\_[tooth]} = \kappa_{slot} \cdot B_{g-slotless} \tag{10}$$

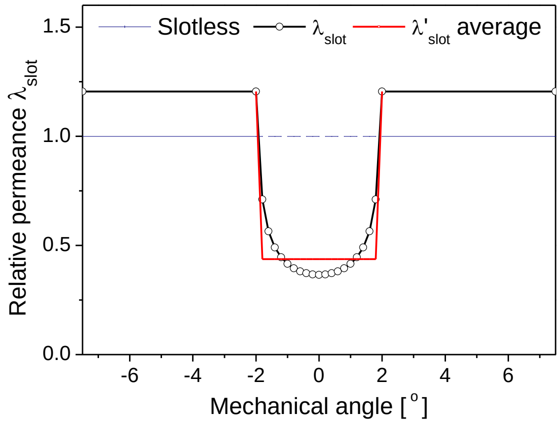


Fig. 5 Relative permeance of slot-opening effect with flux distortion effect

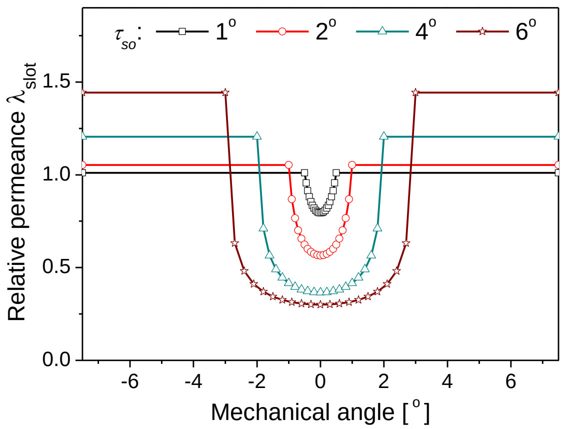


Fig. 6 Analysis of slot-opening effect using refined relative permeance

By utilizing the proposed assistant model, the slot-opening effect on the air gap flux density distribution accounting for flux distortion can be accurately considered by using refined relative permeance method. Then, Fig. 6 gives an analysis of slot-opening effect with different opening width. The proposed concentration factor can be used to consider the effectiveness of magnetic pole-arc in prediction of air gap field in IPMM using basic slotless analytical modeling [6], [7].

III. Results and Discusses

The air gap flux density waveform in the slotless IPM motor model can be assumed to be an approximate trapezium waveform [6], as Fig. 7 illustrates, in which the flux density "B_g" with the magnetic pole-arc "τ_{pole}" represents the magnet flux passes through rotor core and radial disperse into the air gap, while the leakage flux exists in the ribs regions of flux barriers are simplified dealt with its width of "b" and saturated flux density of "B_{sat}". In order to simplify the field analysis in IPMM, some assumptions are made first, as following [7]:

(a). the permeability of iron is infinite.

(b). the rib region is fully saturated at constant value B_{sat}.

(c). the width of rib b is small enough compared to pole-arc.

It is easy to use a lumped circuit method to analyze the magnetic field in slotless IPMM [7], by which the air gap flux density distribution can be well predicted, as Fig. 8 shows. And the air gap flux density in slotted models can be predicted well using improved relative permeance, as Fig. 9 show.

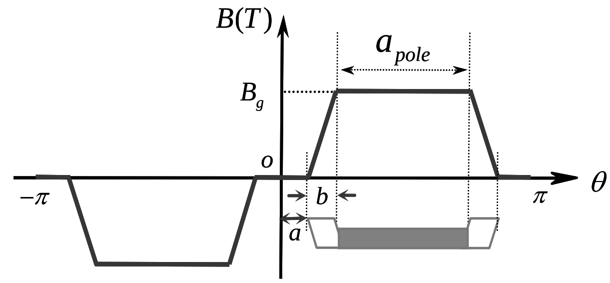


Fig. 7 Assumed air gap flux density distribution in slotless IPM motor

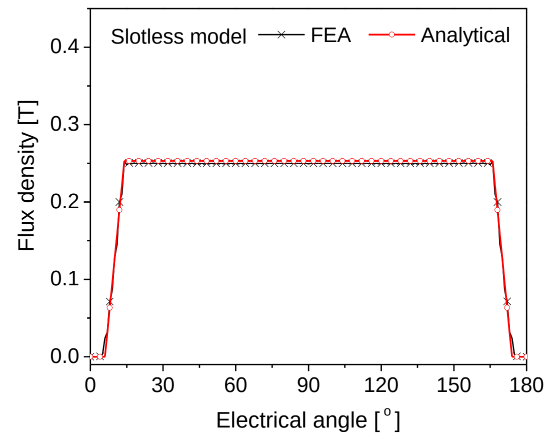
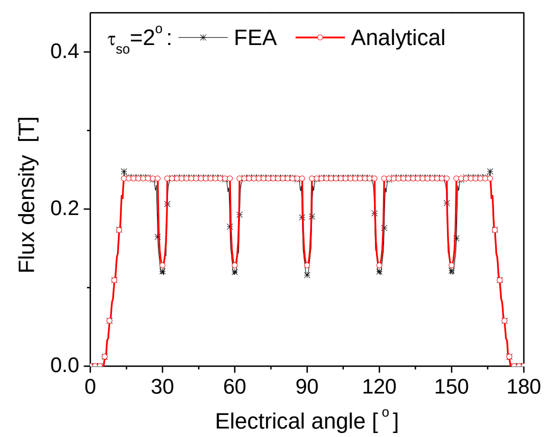
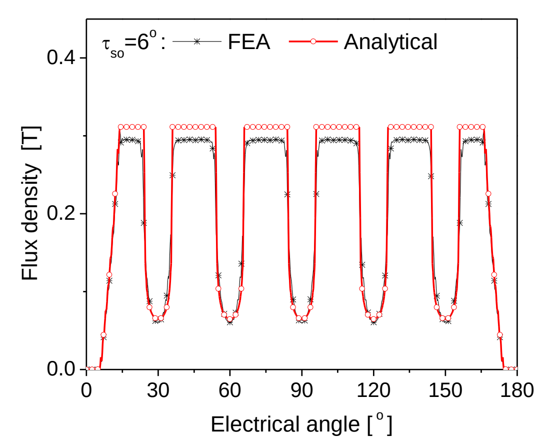


Fig. 8 Comparison of air gap flux density in slotless IPM motor model



(a). with small slot-opening width



(b). with large slot-opening width

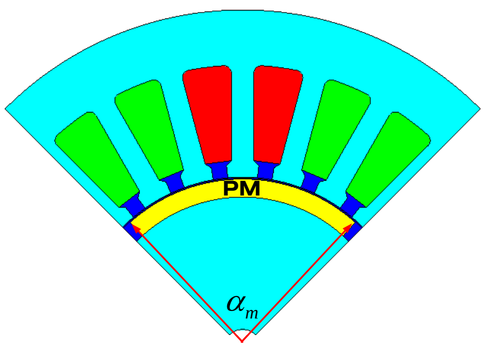
Fig. 9 Prediction of air gap flux density in slotted IPM motor model

Conclusion

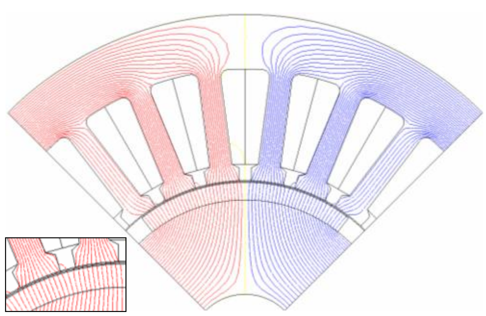
An effective assistant model was proposed to consider the unique slot-opening effect on the air gap field distribution in IPM motor. This analytical modeling describes the magnetic flux distortion phenomenon in IPM rotor core caused by slot-opening and accurately compensates the prediction of air gap flux density with considering the decreased effectiveness of magnet pole-arc. This assistant model helps to apply analytical methods to IPMM design instead of time-consuming FEA.

Appendix

A typical SPMM model is given, as Fig. A1 shows. There isn't flux concentration phenomenon caused by slot-opening effect, as proved by FEA in Fig. A3, the common relative permeance method Fig. 2 and (A1)~(A2), helps to predict the air gap flux density distribution in SPMM, as Fig. A4 gives.



(a). Analysis model of a typical SPMM



(b). Magnet flux distribution in SPM

Fig. A1 Open-circuit analysis of SPMM by FEA

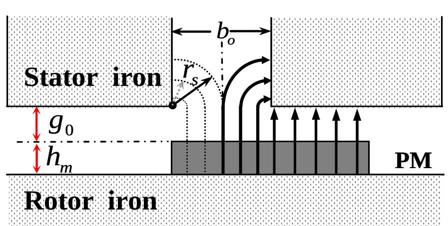


Fig. A2 Analysis model for relative permeance of slot-opening effect in SPM

$$\hat{\lambda}_{slot} = \lambda_{slot} \Big/ \frac{\mu_0}{(g_o + h_m/\mu_r)} \quad \text{(A1)}$$

and

$$\lambda_{slot} = \mu_0 \Big/ \left(g_o + \frac{h_m}{\mu_r} + \frac{2\pi r_s}{4} \right) \quad \text{(A2)}$$

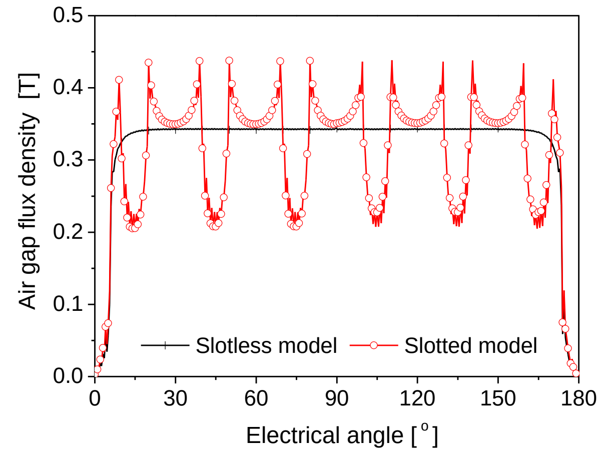


Fig. A3 Comparison of air gap flux density in slotless/slotted SPMM by FEA

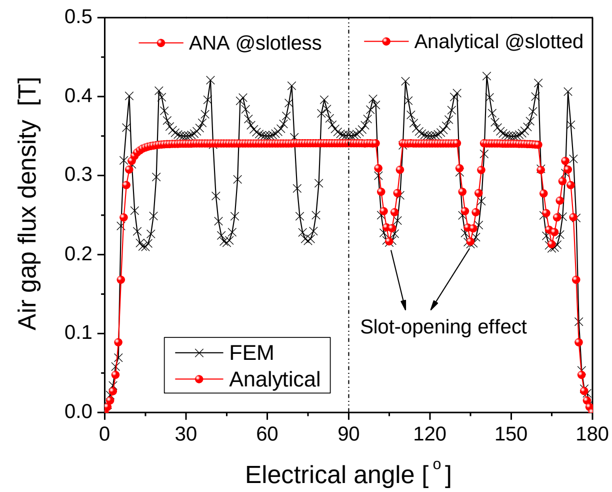


Fig. A4 Comparison of predicted air gap flux density in SPMM with FEA

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