Analysis and Modeling of Stator Slot-Opening Effect on Open-Circuit Air-gap Field Distribution in Interior-type Permanent Magnet Machine

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Abstract — This paper proposes an effective modeling for considering the stator slot-opening effect on air-gap field distribution in conventional interior-type permanent magnet (IPM) machine. Compare to surface-type PM (SPM) machine, an additional significant effect of slot-opening existing in IPM machine, causing concentration of air-gap flux density since the flux path distortion in iron core between the buried PM and rotor surface, which is analyzed and modeled in a simply way for considering effective magnet pole-arc. The validity of this proposed analytical method is applied to predict air-gap flux density distribution in an IPM machine model and well confirmed by 2-dimensional finite element method (FEM).

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, PM brushless machines are increasingly being used in various applications, such as variable-speed drives, servo drives, electric vehicles, and other industrial drives [1].

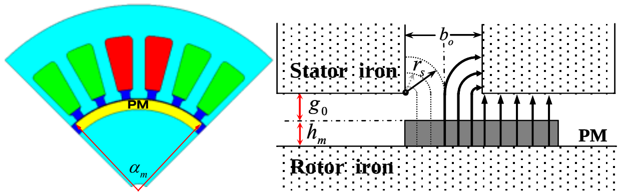
Compared with surface-mounted PM (SPM) machines, interior-type PM (IPM) machines have superior advantages on robust rotor construction and high reluctance torque due to the unique rotor structure that PMs buried inside rotor core [1]. However, the complex rotor structure increases the difficulty and time-consuming in IPM machine designs.

From the previous work [2], a well-accepted analytical model is built to consider the slot-opening effect on the air-gap field distribution in the SPM machines, by proposing permeance λ_{slot} and relative permeance concepts, as equations (1) and (2) defined. Under an assumed field pattern between rotor and stator surfaces, that 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 [2], as Fig. 1 illustrates in a typical SPM motor model.

$$\lambda_{slot} = \mu_0 \Big/ \left(g_o + \frac{h_m}{\mu_r} + \frac{2\pi r_s}{4} \right) \qquad (1)$$

and

$$\hat{\lambda}_{slot} = \lambda_{slot} \Big/ \frac{\mu_0}{(g_o + h_m/\mu_r)} \qquad (2)$$



(a). SPM motor model. (b). assumed flux path for pemeance calculation
Fig. 1. SPM motor model and its slot-opening effect analysis model

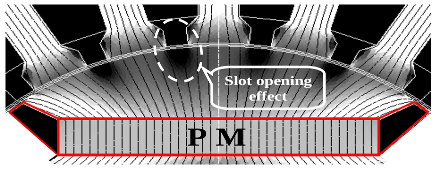


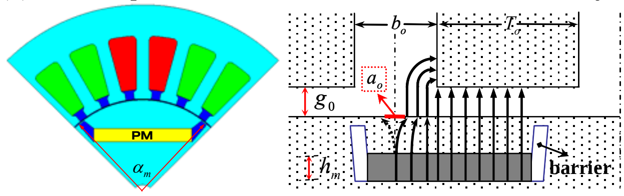
Fig. 2. Flux path distortion in IPM rotor core due to slot-opening effect

As to the SPM motor situation, that flux source (PM) closing to the stator tooth, consequently the slot-opening effect only on the air-gap field region. Differently, the slot-opening effect on both air-gap and rotor core in IPM motor. As Fig. 2 shows, the magnet flux pass through high permeance rotor iron core before crossing rotor surface into air-gap, which results in the flux path distortion that concentrates to the stator teeth regions, while avoiding facing to the slot-opening regions. It is actually reduces the "effective" regions of magnet pole-arc. For considering this unique slot-opening effect phenomenon in IPM motor model, an assistant analytical model is proposed in this paper, which helps to predict the air-gap field distribution more preciously. The validity of proposed analytical model is verified by comparing the analytical results with FEM.

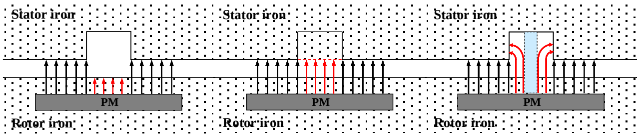
II. SLOT-OPENING EFFECT MODEL IN IPM MACHINE

A 4-pole and 24-slot ($2P=4$, $Q_s=24$) IPM motor model with conventional radial magnetization is built based on the given SPM motor model, that having identical dimensions and differ only in the rotor structure. The distortion of flux path inside the IPM rotor core due to the unique slot opening effect as mentioned above is vividly described in a simplified model, as Fig. 3(b) shows. Except the "α_0" region without out-crossing flux, the effective regions of pole-arc "τ_{pole}" can be determined correspondingly.

However, it is complex to calculate the "α_0" region exactly. Therefore, a simply model is equivalently built, as Fig. 4 shows. Also, a few assumptions are made first in order to simplify the air-gap field analysis:
(a). the permeability of iron is infinite.
(b). the rib region is fully saturated at constant value.
(c). the width of rib b is small enough compared to pole-arc.
(d). the flux pattern inside the IPM rotor is assumed firstly.



(a). IPM motor model, (b). assumed flux path due to slot-opening effect
Fig. 3. IPM motor model and its slot-opening effect analysis model.



(a) (b) (c)

Fig. 4. Modeling of slot-opening effect in IPM motor model, (a). absolute slot-opening effect, (b). none slot-opening effect, (c). trade-off [(a)+(b)]

According to the above proposed models, the PM flux path distribution between the buried PM and stator tooth is assumed based on two ideal situations model (a) and model (b), then the slot-opening effect on magnet pole-arc is considered by a trade-off way, as (c) model illustrates. All of non-effective pole-arc regions "α_o" appeared in per pole-arc are deleted, then the effective pole-arc $\tau_{pole\text{-}effective}$ can be obtained. Furthermore, the effective pole-arc coefficient $\kappa_{effective}$ is defined, as following equations given:

(1). Equivalent slot-opening width: $\alpha_o = \dfrac{b_o + 0}{2} = \dfrac{b_o}{2}$ (3)

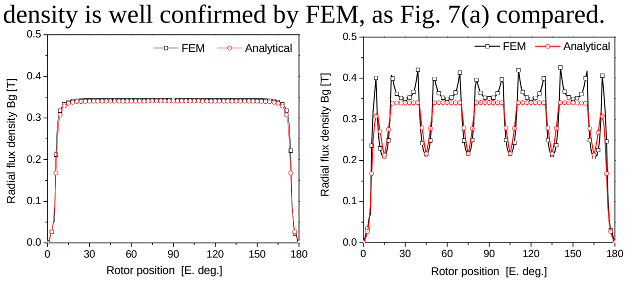
(2). Effective pole-arc: $\tau_{pole\_effective} = \tau_{pole} - (Q_s/2P)\cdot\alpha_o$ (4)

(3). Effective pole-arc coefficient: $\kappa_{effective} = \dfrac{\tau_{effective-pole}}{\tau_{pole}}$ (5)

III. RESULTS COMPARISON AND DISCUSSES

In SPM machine, the air-gap flux density distribution B_g is calculated from the product of the open-circuit field produced by magnets in non-slots model situation and the relative permeance of slot-opening effect λ_{slot} [2]. The slot-opening effect on air-gap flux density in SPM motor model is observed from the results comparison in Fig. 5, that the magnitude of flux density are not changed with and without considering slot-opening effect, since the magnet pole-arc is constant. The analytical results are confirmed by FEM.

In IPM machine, the air-gap flux density distribution B_g is usually calculated by solving equivalent magnetic circuit of non-slots model with a pre-assumed waveform of flux density distribution [3], as Fig. 6 shows. The predicted flux density is well confirmed by FEM, as Fig. 7(a) compared.



(a). analysis in the non-slot model, (b). analysis in the slotting model.

Fig. 5. Results of air-gap field analysis in SPM motor model.

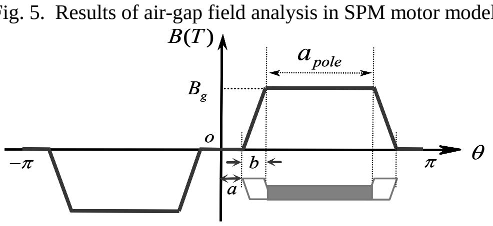
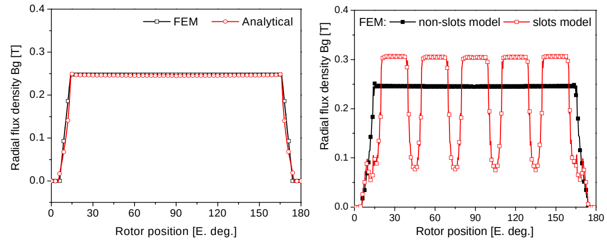


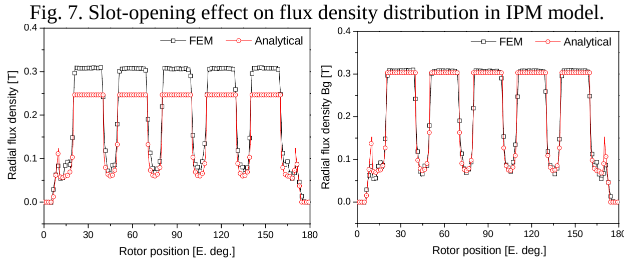
Fig. 6. Assumed one pole-pair flux density waveform in IPM motor model.

where, "a" is gap to the q-axis, "b" corresponds to the rib length of each flux-barrier, "α_{pole}" is visual magnet pole-arc.



(a). analysis in non-slot model. (b). slot-opening effect confirm.

Fig. 7. Slot-opening effect on flux density distribution in IPM model.



(a). effective pole-arc is not considered (b). effective pole-arc is considered

Fig. 8. Effective pole-arc effect on flux density distribution in IPM model.

In Fig. 7(b), it is easy to confirm by FEM, that the magnitudes of flux density are different with and without including slot-opening effect. For compensating this difference, the unique slot-opening effect is considered in two steps. Firstly, the predicted slotless flux density distribution only coupled with relative permence of slot-opening, which obtained by using conforming mapping method [4], the usual slot-opening effect is considered, while the magnitude of flux density is lower then the FEM result, as Fig. 8(a) shows. Then, secondly, the proposed effective pole-arc coefficient $\kappa_{effective}$ is used for considering the concentration of pole flux. In general, the air-gap flux density distribution is predicted by producing the slotless flux density distribution, relative permeance of slot-opening and effective pole-arc coefficient, as Fig. 8(b) verified.

IV. CONCLUSION

An effective analytical modeling for considering the unique slot-opening effect on air-gap field distribution in IPM machine was presented. This analytical model can well describe the unique phenomenon of effective magnet pole-arc reduction caused by the flux path distortion insider IPM rotor core, and furthermore equivalently compensates the enhancement of air-gap flux density. Therefore, with the help of this analytical model, the air-gap flux density distribution in IPM machine can be predicted more exactly, which has been well confirmed by 2-dimensional FEM.

V. REFERENCES

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