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매입형 영구자석 전동기의 Slot-opening Effect에 관한 연구

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A Study on Slot-opening Effect in Interior Permanent Magnet Motor

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Abstract - In this paper, the variation of air-gap field intensity caused by the slot-opening in interior permanent magnet (IPM) motor is investigated, which is for predicting the instantaneous magnetic field more preciously in analytical method further. It is different with the approach of dealing the slot-opening effect on the air-gap field distribution with the "relative permeance" function in surface permanent magnet (SPM) motor. The prediction of the air-gap field in IPM motor is much more complex than SPM motor. In this study, an approximate estimation method is adopted based on analyzing the changing of flux path in both the IPM rotor part and stator part, and in additional an analytical function defined as "relative pole-arc" is built. The finite element method(FEM) is used for confirming the slot-opening effect on the field prediction.

1. INTRODUCTION

In recent years, the interior permanent magnet(IPM) motors attract much more interests for their superior characteristics, such as high efficiency, high power density, and wide constant-power speed range. For satisfying different requirement, such as hybrid and electric vehicle(HEV) propulsion, the public welfare and industrial use, the design of IPM motor is the primary work, also the complex process.

In structure, the IPM motors have inherent advantages over the surface permanent magnet (SPM) motors. The IPM motors have PMs buried inside the rotor core, which is not only for avoiding the separation of magnets at the high speed, but also for utilizing the hybrid torque component, name as magnet torque and reluctance torque[1]. The IPM motor performances in essence are relate to the rotor structure design closely.

The magnetic field distribution in the IPM motor is quite sensitive to the geometry of the rotor and stator due to the small air-gap[2]. Consequently, it is necessary to find high precision analytical method for predicting the air-gap field distribution in the IPM motor. An well analytical method can save a huge time in the motor initial design.

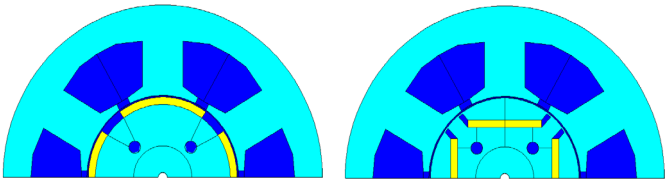
The prediction of air-gap field in IPM motor is much more complx than in SPM motors, because of the complex IPM rotor structure.

Stator slot-opening effect on the field distribution has been researched and well reported a lot in SPM motor model. The series study on the instantaneous magnetic field distribution in brushless SPM motor [2], [3], [4] proposes the perfect method for considering the stator slot-opening effect on the field prediction. In those study, the 2-d "relative permeance" function is introduced, which is based on the calculation of effective length of flux paths between the rotor and stator. But the study of slot-opening effect in IPM motor model has not been completed, a lot of work should be research. This study is just basic prepare for developing the analytical prediction of field distribution in IPM motor.

2. ANALYSIS and MODEL

2.1 PM Motor Model

Fig. 1 shows two PM motor models, Surface type and Interior type models. These two models have the same stator structure, and also have the same pole-pitch of the PM in rotor part for simplicity in the following study.



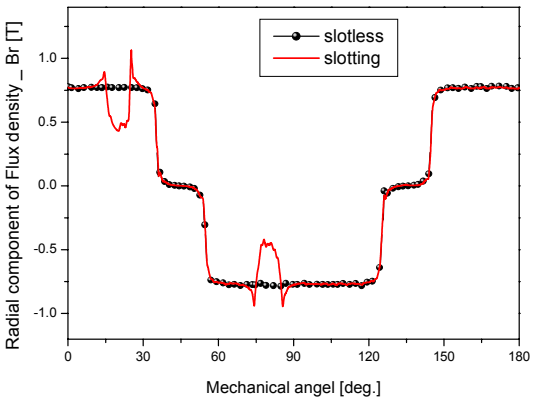
(a) SPM motor model (b) IPM motor model
<Fig. 1> Analysis models of PM motor

2.1.1 Slot-opening Effect in SPM Motor

According to the method of "relative permeance" function proposed in [1], [2], the magnetic field in the air-gap region of a radial-field SPM motor is predicted as function (1) shows, that the flux density B_g produced by the surface mounted PM with assuming a smooth stator, and then modified by a relative permeance function, i. e.

$$B_g' = B_g \times \tilde{\lambda}_{slot-opening} \quad (1)$$

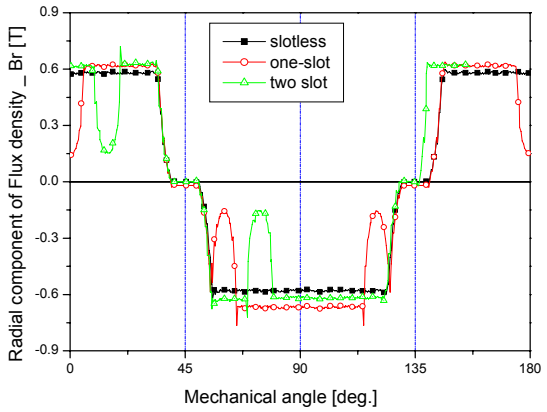
where, the B_g' is the open-circuit field distribution in the air-gap region, B_g is the field distribution with smooth stator surface, and $\lambda_{slot-opening}$ is the relative permeance function of the slot-opening regions. As the function (1) shows, the air-gap field distribution accounting for slot-opening effect is predicted as the following Fig. 1 shows. It can be well observed in the comparison of flux density distribution of B_g and B_g', that both of the amplitude of the flux density are almost the same That means in SPM motor, the slot-opening effect is limited only on the opening region of stator slot, but no effect on the other areas of field distribution.



<Fig. 2> Radial component of Flux density distribution in air-gap region of SPM motor model

2.1.2 Slot-opening Effect in IPM motor

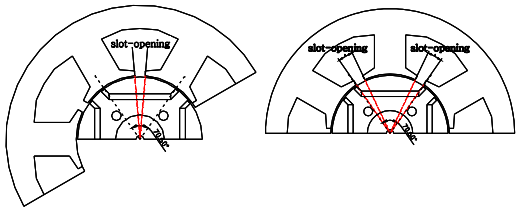
In IPM motor, the magnetic field in the air-gap region is produced by the PM buried inside rotor core, as the Fig. 1 shows. Therefore, the flux path from the PMs to the stator teeth is composed of two part, air-gap and core region.



<Fig. 3> Radial component of Flux density distribution in air-gap region of IPM motor model

2.2 "Relative pole-arc" of IPM Motor

For dealing with the variation of amplitude of flux density, in this paper an approximate method is proposed. It is based on the estimation of the effective flux path between the rotor and stator in term of pole arc. If assuming a smooth stator face, the flux produced by the buried PM pass through the air-gap region in full pole-arc, that means stator having the same arc face to the rotor for flux entering to the stator core. With the consideration of slot-opening effect, the stator has partly surface for rotor flux entering into the stator core. Fig. 3 shows the movement of one and two slot-opening regions appearing in one magnet pole-arc region. Because of the low permeability of slot-opening regions, the rotor flux entering to the stator mainly from the stator teeth part. For the same amount of flux produced by the buried PM, the narrowing flux path because of slot-opening results in the enhancing of the amplitude of flux density, as the Fig. 3 shows.



<Fig. 4> IPM Model with one slot-opening and two slot-opening region moving into a magnet pole-arc

The effective pole-arc in IPM rotor is determined as the function (2), name as "relative pole-arc". Base on the flux path consideration, the relative pole-arc of the analysis IPM motor model is estimated.

$$\tilde{P}_{relative} = P_{IPM-rotor} \times \frac{1}{2} P_{slot-opening} \qquad (2)$$

According to the positions of the slot-opening appearing in each pole of IPM rotor, the relative pole-are can be calculated, as following. The residual of buried PM is assumed to be 1.0, and the relative permeance of PM is also considered to be 1.0 for simplicity.

<Table 1> The results of "relative pole-arc"

Slot-opening appearance	IPM rotor pole-pitch (deg.)	Relative pole-arc (deg.)
No slot-opening	70.6	70.6
one slot-opening	70.6	65.8
two slot-opening	70.6	61.7

And then, the variation of the amplitude of flux density can be predicted. The "relative pole-arc" $\tilde{P}$ is used to modify the amplitude of the flux density B_g produced by the buried PM in the rotor core with smooth stator assuming, as given,

$$A_g' = A_g \times (P_{IPM-rotor} / \tilde{P}_{relative}) \qquad (3)$$

<Table 2> The comparison of amplitude of flux density

Slot-opening appearance	Predict value A_g' (T)	FEM A_g' (T)
No slot-opening	0.58	0.58
one slot-opening	0.62	0.622
two slot-opening	0.67	0.68

where, the A_g' is the predict amplitude of flux density, and A_g is the amplitude of B_g without consideration of slot-opening effect. Then, with the help of FEM, the verification of this proposed approximate calculation is give as the comparison of the predict value and FEM results by using the analysis IPM motor model.

2.2.2 Variation of Slot-opening Width

From the analysis of the proposed prediction, the width of slot-opening has effect on the variation of amplitude of flux density. The proposed prediction method is applied into the following model with the variation of slot-opening width, and the comparison are list in the following Tables.

<Table 3> comparison of one slot-opening effect results

Slot-opening width (deg.)	Predict value A_g' (T)	FEM A_g' (T)
8	0.610	0.603
12	0.632	0.626
14	0.643	0.639

<Table 4> comparison of two slot-opening effect results

Slot-opening width (deg.)	Predict value A_g' (T)	FEM A_g' (T)
8	0.650	0.642
12	0.698	0.695
14	0.723	0.720

3. CONCLUSION

In this study, the stator slot-opening effect on the air-gap field distribution of the IPM motor is dealt with the proposed method of "relative pole-arc" estimation. According to the relative position of the slot-opening to each PM pole, the amplitude of predicted flux density is modified. The feasibility of this method is proved by the results comparisons with the help of FEM. By connecting this proposed method with the analytical method that predicting the air-gap field distribution produced by the buried PM inside rotor core[5], a more accurate can be obtained, further it help to calculate the instantaneous characteristics of the magnetic field in IPM motor.

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