매입형 영구자석 전동기에서 무부하시 공극 자속밀도 분포에 대한 Slot-Opening Effect를 고려한 보조 모델

논 문
60-4-12

Assistant Model For Considering Slot-Opening Effect on No-load Air-gap Flux Density Distribution in Interior-type Permanent Magnet Motor

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(Liang Fang · Do-Jin Kim · Jung-Pyo Hong)

Abstract – This paper proposes an effective assistant model for considering the stator slot-opening effect on air gap flux density distribution in conventional interior-type permanent magnet (IPM) motor. Different from the conventional slot-opening effect analysis in surface-type PM (SPM) motor, a composite effect of slot-opening uniquely existing in IPM motor, which additionally causes enhancement of air gap flux density due to magnet flux path distortion in iron core between the buried PM and rotor surface. This phenomenon is represented by a proposed assistant model, which simply deals with this additional effect by modifying magnetic pole-arc using an effective method. The validity of this proposed analytical model is applied to predict the air gap flux density distribution in an IPM motor model and confirmed by finite element method (FEM).

Key Words : Assistant model, Analytical method, Effective magnetic pole-arc, FEM, SPM/IPM motor

1. Introduction

In recent years, the permanent magnet (PM) machines are widely used in various applications because they offer excellent maintainability, controllability, and environmental endurance while providing high-efficiency operation with high power factor [1]. More and more attentions are paid to various kinds of PM machine designs. And many analytical methods are proposed and successfully applied to the PM machine designs, which can largely alleviate the time-consuming FEM computation. Majority of well developed analytical method are verified to be suitable for the surface-mounted PM (SPM) design machines, but not suitable for interior-type PM (IPM) design machines. Compared with SPM machines, the IPM machine have superior advantages on robust rotor construction and high reluctance torque due to the unique rotor structure that PMs buried inside rotor core [1]. Therefore, effective analytical methods used for IPM design machine are quite desired for satisfying the growing demands of IPM machine research. However, the complex rotor structure and significant flux saturation increase the difficulty of build analytical model for IPM machine analysis [2].

Due to different machine structures, the flux path pattern inside SPM motor and IPM motor are quite different. In SPM motor situation, the PMs are mounted on the rotor surface, closely facing to the stator surface, therefore, the magnet flux almost straightly crosses the small mechanical air gap and enters into the stator surface. But in IPM motor situation, the PMs are buried insider the rotor iron core, and rotor iron surface closely facing to the stator surface, therefore, the magnet flux should pass through the high permeance rotor iron core before out-crossing rotor surface into air gap, and then enters into the stator surface. This different flux pattern in IPM motor causes the unique phenomenon of flux path distortion insider rotor core due to stator slot-opening effect, which furthermore concentrates the magnet flux enter into air gap by actually reduces the "effective" regions of magnet pole-arc. For considering this unique slot-opening effect phenomenon in IPM motor, an assistant analytical model is proposed in this paper. The validity of proposed analytical model is verified by comparing the analytical results with FEM.

2. Models, Analysis and Results

The stator slot-opening takes simple effect only on air gap field distribution in SPM motor situation since the flux source of PMs are very closed to the stator slots, but it takes a composite effect on flux density distribution of both air gap field and rotor core field due to the interior PM rotor structure. The difference of the

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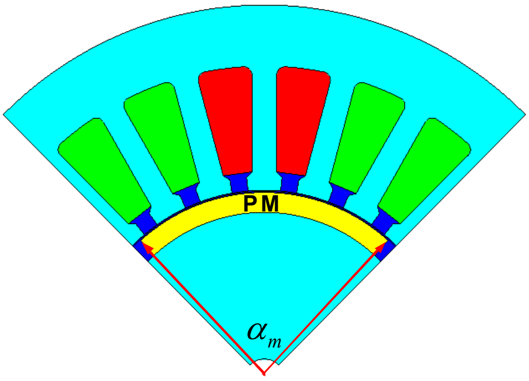
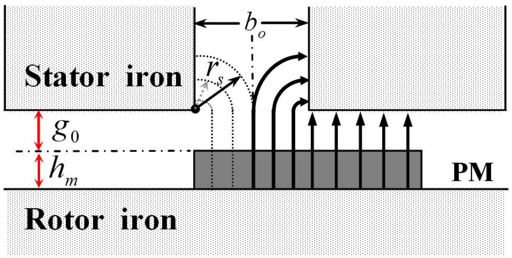


(a) Analysis model of a SPM motor



(b) Assumed flux path for permeance calculation

Fig. 1 SPM motor model and slot-opening effect analysis model

stator slot-opening effect consideration are comparatively studied in given analysis models, and an effective assistant model is proposed to consider the additional effect of slot-opening on the IPM rotor inside field, and helps to predict the air gap flux density distribution in IPM motor using a similar way of SPM motor situation.

2.1 Slot-Opening Effect Analysis in SPM Motor

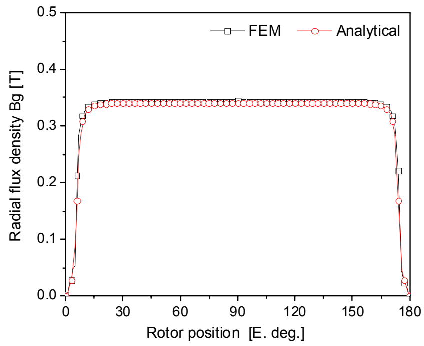
A typical SPM motor model with 4-pole/24-slot ($2P$=4/Q_s=24) design is built, as Fig. 1(a) shows. TABLE I. lists its dimensions and parameters (in Appendix). As the previous work [3], air gap flux density distribution can be well determined from the product of magnetic field produced by PM and relative permeance of slotting stator surface. The no-load air gap field prediction without considering slot-opening effect can be well predicted by various methods, such as space harmonic analysis [2] and lumped-parameter magnetic circuit [3], which is not focused in this study. The slot-opening effect on air gap flux density distribution is investigated. Under an assumed field pattern between PM-mounted 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, centered about the corner of a tooth, wherever a magnet faces a slot-opening, as Fig. 1(b) illustrates, the conventional slot-opening effect on air gap flux density distribution is considered by utilizing the technique of permeance λ_{slot}, and relative permeance $\hat{\lambda}_{slot}$, as following equations defined, respectively.

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

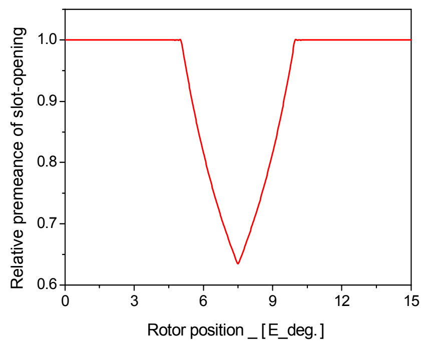
and

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

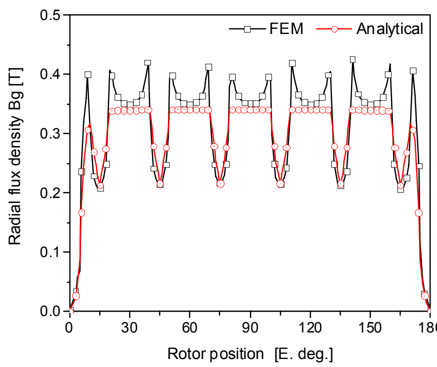
As mentioned above, the no-load air gap flux density without/with considering slot-opening effect are calculated by mentioned process and well verified by FEM, as Fig. 2 shows respectively. Obviously, it can be found that amplitude of flux density are not changed in SPM motor analysis without/with considering slot-opening effect.



(a) flux density in non-slot SPM motor model

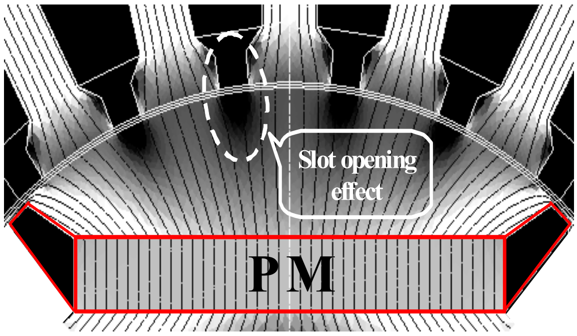


(b) relative permeance of one slot pitch region

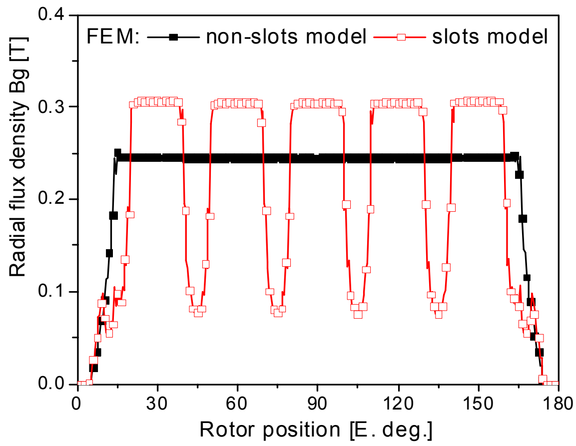


(c) flux density in slotting model

Fig. 2 Air gap flux density distribution without and with considering slot-opening effect in SPM motor model



(a) flux path distortion in IPM rotor core due to slot-opening effect



(b) composite slot-opening effect in IPM motor

Fig. 3 Slot-opening effect on rotor core and air gap fields distribution in IPM motor model by FEM

2.2 Slot-Opening Effect Analysis in IPM Motor

A comparative 4-pole/24-slot IPM motor model is built based on the given SPM motor model, as Fig. 4(a) shows, that having identical contour dimensions and conventional radial magnetized PM buried in rotor core. TABLE I. lists its dimensions and parameters together with the presented SPM motor model.

As mentioned, the flux path inside IPM rotor iron core emerges distortion due to slot-opening effect, which can be directly observed from the results of FEM, as Fig. 3(a) shows, that the magnet flux concentrates on the directions facing to stator teeth regions, while avoiding facing to the slot-opening regions when crossing through high permeance rotor iron core before out-crossing rotor surface into air gap. Different from the SPM motor analysis, the air gap flux density result obtained from slots model analysis by FEM shows higher amplitude values than from non-slot model analysis, as Fig. 3(b), which confirms that slot-opening has additional effect on reinforcing air gap field in IPM motor situation.

In order to simplify the air gap field analysis in IPM motor model, a few assumptions are made first :

(a). the permeability of iron is infinite.

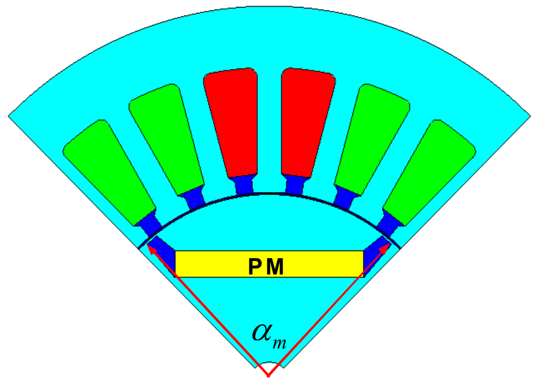
(b). the rib region is fully saturated at constant value.

(c). the width of rib "b" is small enough compared to magnetic pole-arc τ_{pole}. [4]

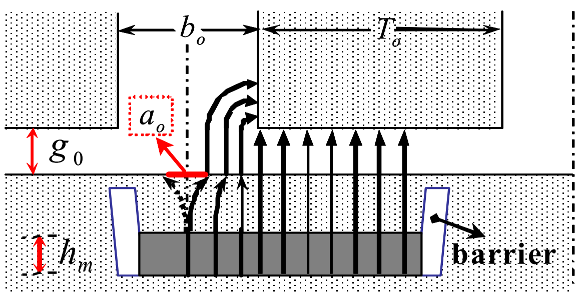
(d). the flux pattern inside the IPM rotor is assumed in a simply pattern as given later.

2.2.1 Assistant Model of Slot-opening Effect Analysis

The flux distortion in IPM rotor core is vividly represented in an idealised model, Fig. 4(b) shows, in which the "a_o" region shows none out-crossing magnet flux, therefore the effective regions of visual magnet pole-arc "τ_{pole}" can be determined by eliminating all "a_o" regions. However, it is very complex to exactly determine the "a_o" region. Therefore, a simple technique is adopted to estimate the non-effective region "a_o" in this study. In Fig. 5 presented models, the magnet flux path distribution between the buried PM and stator tooth is decomposed into two limit cases, model (a) of total slot-opening effect consideration case, that flux pass through stator tooth into stator, and model (b) of none slot-opening effect consideration case, that stator surface is smooth.

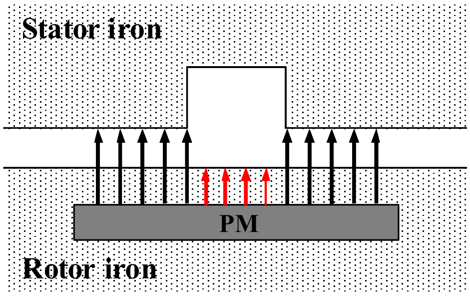


(a) analysis model of an IPM motor

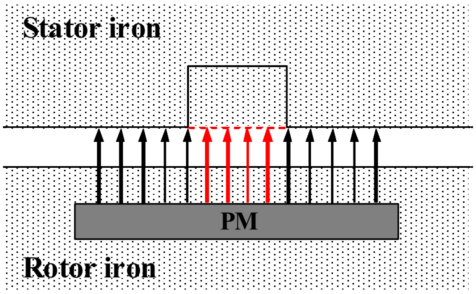


(b) represented of flux path in IPM motor model

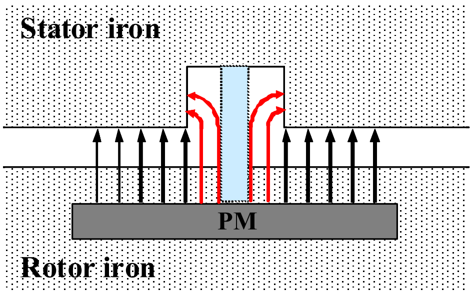
Fig. 4 IPM motor model and original slot-opening effect analysis model



(a) total slot-opening effect



(b) none slot-opening effect



(c) trade-off consideration [(a)+(b)]/2

Fig. 5 Simplified assistant model of slot-opening effect analysis in IPM motor model

By choosing a trade-off way, the slot-opening effect on reduction of visual magnetic pole-arc is dealt, as model (c) illustrates, that a compromise model is used to determine the non-effective region "α_o", as equation (3) gives. All of non-effective pole-arc regions "α_o" appeared in single pole-arc "τ_{pole}" should be eliminated, so that the effective pole-arc "$\tau_{pole\text{-}effective}$" can be determined, as equation (4) gives. Furthermore, the effective pole-arc coefficient "$k_{effective}$" can be defined using equation (5). The (c) model can be used as an assistant model for compensating the difference of amplitude of air gap flux density in prediction.

(a) Compromised non-effective magnetic pole-arc width:

$$\alpha_o = \frac{b_0 + 0}{2} = \frac{b_0}{2} \tag{3}$$

(b) Effective pole-arc considering slot-opening effect:

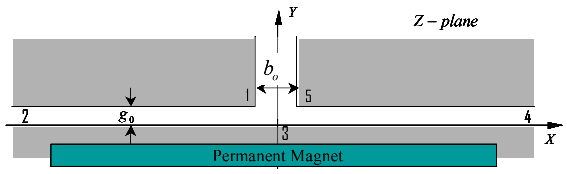
$$\tau_{pole\_effective} = \tau_{pole} - \left(\frac{Q_s}{2P}\right) \bullet \alpha_o \tag{4}$$

(c) Effective pole-arc coefficient:

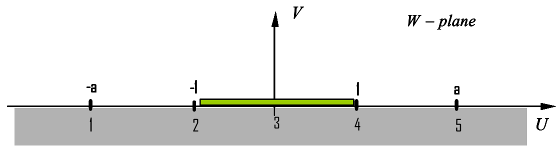
$$k_{effective} = \frac{\tau_{pole}}{\tau_{pole\_effective}} \tag{5}$$

2.2.2 Basic Model of Slot-opening Effect Analysis

Referring to presented work [6], conformal mapping (CM) technique is well applied to deal with slot-opening effect on the air gap field distribution in IPM motor. By performing CM obtained from Schwarz-Christoffel transform theory [5], [6] as equation (6) shows, the air gap connects with single slot-opening (as the interior polygon created by the path (1-2-3-4-5) in original Z-plane, Fig. 6(a) shows) is transformed to another complex upper half-plane (corresponding to the path (1-2-3-4-5) in W-plane, Fig. 6(b) shows), in which the flux source (PM) is replaced by a equivalent current sheet. Then, the magnetic field distribution is equivalently analyzed in the simple W-plane. The relative permeance technique is adopted to consider slot-opening effect on air gap flux density distribution, as equation (8) gives.



(a) configuration of simplified air gap with one slot-opening



(b) transformed region of above air gap/one slot-opening

Fig. 6 Conformal mapping of IPM model stator slot-opening

$$z(x,y) = f[w(u,v)]$$
$$= \frac{2g_0}{\pi}\left[\frac{b_o}{2g_0}\arcsin\frac{w}{a} + \frac{1}{2}\log\frac{\sqrt{a^2-w^2}+\dfrac{2g_0 w}{b_o}}{\sqrt{a^2-w^2}-\dfrac{2g_0 w}{b_o}}\right] \tag{6}$$

where

$$a = \sqrt{1+\left(\frac{2g_0}{b_o}\right)^2} \tag{7}$$

$$\hat{\lambda}_{slot} = \frac{\lambda_{slot}}{(\mu_0/g_0)} = \frac{\left(2\mu_0\Big/\left(b_o\sqrt{a^2-w^2}\right)\right)}{(\mu_0/g_0)} \tag{8}$$

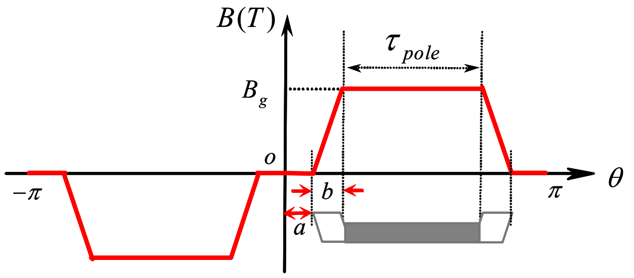


Fig. 7 Assumed air gap flux density distribution in non-slot IPM motor with considering rib regions

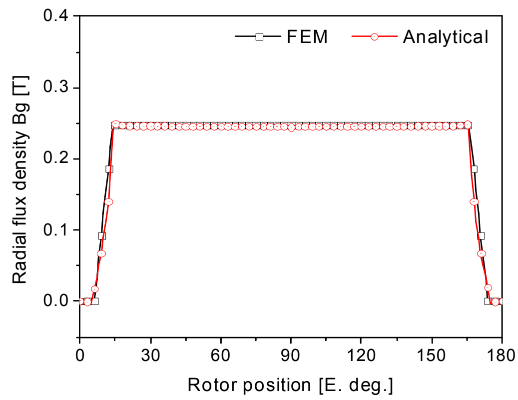
2.2.3 Air gap Flux Density Distribution in Non-Slot IPM Motor

In the IPM motor model, as Fig. 4(a) gives, the air gap flux density distribution without considering stator slot-opening effect can be assumed to be a approximate trapezium waveform [7], as Fig. 7 illustrates, that the magnet flux passing through rotor core and radially dispersing into the air gap is represented by flux density B_g and magnetic pole-arc "τ_{pole}", while the leakage flux exists in the ribs regions of flux barriers are simplified dealt with its width of "b" and saturated value "B_{sat}" according to the B-H characteristics of rib core material.

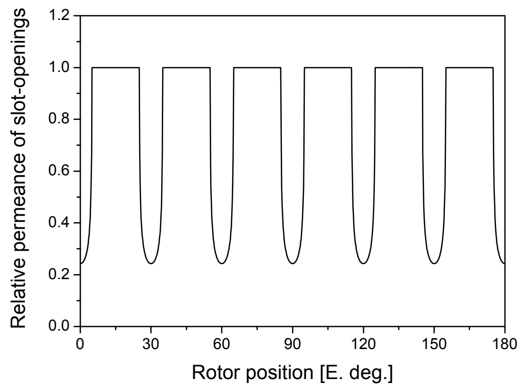
It is easy to use a lumped-parameter magnetic circuit to analyze the magnetic field inside IPM motor. And flux density distribution as the assumed waveform can be determined by the given parameters in Fig. 7 [1].

2.2.4 Results Analysis and Discusses

From present above, the air gap flux density distribution in IPM motor model predicted by solving magnetic circuit of slotless model based on pre-assumed waveform is obtained and well confirmed by FEM, as Fig. 8(a) shows. On the other hand, the basic slot-opening effect on the contour of air gap flux density distribution considered by relative permeance obtain by performing conformal mapping method is shown in Fig. 8(b). If the air gap field is determined from the product the non-slot flux density distribution and relative permeance of basic slot-opening effect, without considering the effective magnetic pole-arc, the air gap flux density distribution is obtained, as Fig. 9(a) shows. The difference between the calculated result and FEM result can be observed. It is different with the SPM motor situation, that the slot-opening effect on air gap flux density distribution do not influence the amplitude of flux density due to its constant magnetic pole-arc "τ_{pole}" whether the slot-opening effect is considered or not. In IPM motor situation, the effective reduction of magnetic pole-arc should be considered, especially in the large (Q_s/pole) situation. Therefore, by using the effective pole-arc coefficient "$K_{effective}$" obtained from proposed assistant model, the predicted air gap flux density in Fig. 9(a) is properly compensated and well confirmed by FEM, as Fig. 9(b) shows.

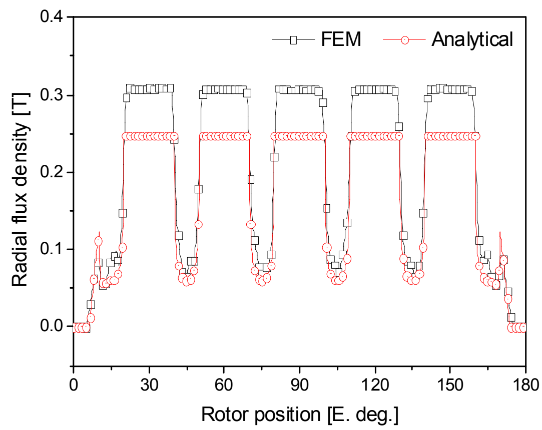


(a) air gap flux density distribution in non-slot model

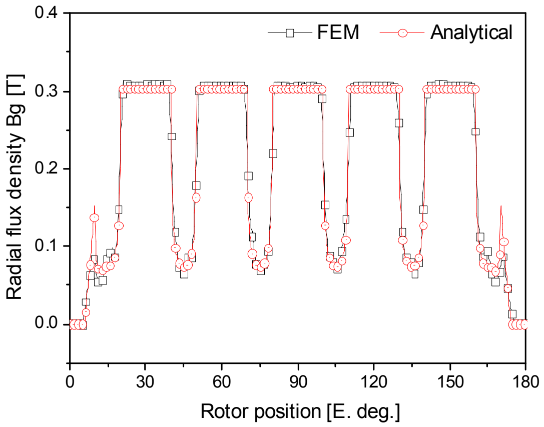


(b) relative permeance of one pole-pitch slot-opening

Fig. 8 Air gap flux density distribution in slotless IPM motor model and stator slot-opening effect consideration by relative permeance method.



(a) Effective pole-arc is not considered



(b) Effective pole-arc is considered by $k_{effective}$

Fig. 9 Air gap flux density distribution with slot-opening effect consideration in slotting IPM motor model.

Table 1 List Symbols and Model Parameters

Item	Unit	SPM model	IPM model
Inner radius of stator	mm	45.5	
Outer Radius of rotor	mm	45.0	
Length of air gap	mm	0.5	
Stack length	mm	100	
Slot-opening width	mm	4.0	
PM segment dimension (one piece)	mm	4.8 (Thick)	46.0 (Length)
	mm		6.5 (Thick)
Magnetic Pole-arc	degree	84 (Mech.)	
PM remanent induction	T	0.4	
Pole / Slot numbers		4 / 24	
Vacuum permeability	H/m	$\mu_0 (4\pi \times 10^{-7})$	
PM relative permeability	H/m	$1.1\mu_0$	

3. Conclusion

This paper proposed an effective assistant model for considering composite effect of stator slot-opening on air gap flux density distribution in IPM motor. The assistant model simply describes the unique phenomenon of magnet flux distortion inside rotor core caused by stator slot-opening effect and generally estimates the effective reduction of magnetic pole-arc for compensating the amplitude of air gap flux density predicted analytically. In conclusion, with the help of proposed assistant model, the air gap flux density distribution in IPM motor can be predicted more accurately. The assistant model is indispensable expecially for the IPM motors having large slot number per pole-arc and/or wide slot-opening width.

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