

A Novel Method for Calculating Airgap Permeance of PM Machines Based on Equivalent Electrostatic FEA

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The detailed airgap permeance distribution of an electric machine is important information for analyzing and optimizing the machine's performance. However, there is only analytical method to calculate permeance, and the simulation method which can be used to validate the analytical method for permeance is not given. In this paper, a novel simulation method for investigating the airgap field of PM machines is proposed based on the duality of magnetic field and electric field. Through equivalent electrostatic finite element analysis (FEA), the airgap permeance of the PM machine can be easily determined. The obtained permeance distribution can then be associated with analytical form of magnetomotive force (MMF) to further calculate the airgap flux density. The proposed method can take the stator slotting effect into account, and its effectiveness is validated on a vernier PM machine. Finally, the reasonability of the method on calculating airgap permeance is verified through comparison with a proposed 3D electromagnetic FEA.

Index Terms—PM machine, airgap flux density, permeance, electrostatic field.

I. INTRODUCTION

IN order to predict the PM machine performance, it is essential to analyze the magnetic field distribution in the airgap. Due to the stator slotting effect and rotor saliency, the modeling of flux-path permeance is the key to obtain the airgap field precisely. Specially, to investigate the mechanism of some novel machine topologies, such as magnetic geared machines, vernier PM machines, etc., it is of great importance to get detailed knowledge of the airgap permeance. In recent years, a variety of analytical methods for modeling the airgap permeance have been proposed [1]. Generally, the magnetic-circuit based methods are most commonly adopted [1-3].

In this paper, a simulation method for investigating the airgap field of PM machines is proposed. The airgap permeance distribution is calculated through electrostatic FEA. The principle of this method will be introduced in Section II. Section III will be devoted to validation of this method. Finally, a 3D FEA in the electromagnetic field will be conducted to further verify the reasonability of the proposed method.

II. PRINCIPLE AND IMPLEMENTATION

Fig. 1(a) shows the electromagnetic model of a PM machine. The relative permeability of the core and PM material are assumed infinite and equal to that of the airgap respectively for simplification. Fig. 1(b) gives the sketch of a corresponding electrostatic model. The core and magnet materials are changed to copper and air, respectively. It should be noted that only the radial component is considered in the following field analysis.

For the stator slotted PM machine, the airgap permeance per unit area Λ is a function of position angle θ_s and can be expressed by (1), where $d(\theta_s)$ is the length of flux path in the airgap. Consider a constant magnetic potential difference ΔF between the stator and rotor, the permeance distribution can be obtained by evaluating the field intensity $H(\theta_s)$ as given in (2). However, according to Gauss's Law, the divergence of magnetic field is zero, and the magnetic potential of any closed surface could not possibly be a constant non-zero value. Hence, the simple calculation process of (2) cannot be achieved in 2D

magnetic field FEA. In literature, the airgap permeance is always evaluated by geometric methods such as conforming transformation [2].

Nevertheless, when the machine topology is analyzed in electrostatic field as shown in Fig. 1(b), the permeance distribution can be easily obtained in an equivalent way. As electrostatic field is with non-zero divergence, a constant electrical potential difference between the stator and rotor can be set. Then, $d(\theta_s)$ can be investigated by evaluating electric field intensity $E(\theta_s)$ acquired by FEA. Finally, based on (3) the airgap permeance of the original electromagnetic model can be calculated. Essentially, the proposed method takes advantage of the duality between magnetic field and electric field.

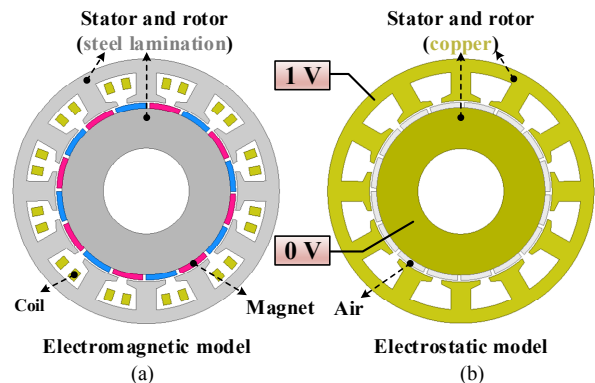


Fig. 1. The sketch of the proposed method for calculating airgap permeance.

$$\Lambda(\theta_s) = \frac{\mu_0}{d(\theta_s)} \quad (1)$$

$$\Delta F = H(\theta_s) \cdot d(\theta_s) \Rightarrow \Lambda(\theta_s) = \mu_0 \frac{H(\theta_s)}{\Delta F} \quad (2)$$

$$\Delta U = E(\theta_s) \cdot d(\theta_s) \Rightarrow \Lambda(\theta_s) = \mu_0 \frac{E(\theta_s)}{\Delta U} \quad (3)$$

III. EFFECTIVENESS VALIDATION

In this section, the proposed method is applied to a vernier PM machine as shown in Fig. 2, with its parameters listed in Table I. The rotor MMF can be analytically determined by (4).

When the airgap permeance $\Lambda(\theta_s)$ is obtained from the electrostatic field analysis, the resulting no load airgap field distribution can be calculated by (5). Then, the flux density from this proposed method is compared with that from classic electromagnetic FEA, as given in Fig. (3). It can be seen that obtained airgap field has relatively high accuracy. Therefore, the effectiveness of the proposed method for calculating airgap permeance is validated indirectly.

$$F_c(\theta_s, t) = \sum_{i=1,3,5,\dots} \frac{4}{\pi} \frac{B_r}{i \mu_0 \mu_r} h_m \sin(i\alpha \frac{\pi}{2}) \cos(iP_r \theta_s - i\omega t) \quad (4)$$

$$B_g(\theta_s, t) = F_c(\theta_s, t) \Lambda(\theta_s) \quad (5)$$

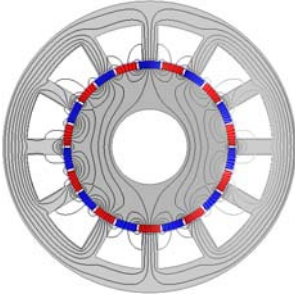


Fig. 2. Flux distribution of a vernier PM machine by electromagnetic FEA.

Item	Value
Outer diameter	62mm
Inner diameter	37.2mm
Airgap length	0.8mm
Slot opening	6.62mm
Slot depth	15.0mm
PM thickness	2.5mm
PM pole arc	0.9
PM remeance	1.13
PM material	N40UH
Core material	50WW470

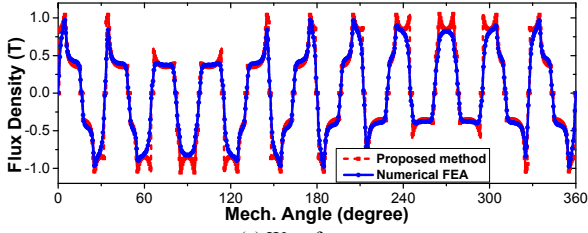


Fig. 3. Waveform and FFT Comparison of no load airgap flux density obtained from the proposed method and numerical electromagnetic FEA.

IV. DUALITY VERIFICATION OF THE ELECTROSTATIC AND 3D ELECTROMAGNETIC FEA ON CALCULATING PERMEANCE

In order to further evaluate the reasonability of the electrostatic method, a 3D-magnetic-field FEA method for calculating airgap permeance is proposed, as illustrated in Fig. (4). From the left view of Fig. (4), it can be seen that the 2D vernier machine in Fig. 2 is extruded into a 3D topology. While seen from the right view, the 3D vernier machine is coaxially connected to a homopolar machine topology. The DC current in the winding can then establish a homopolar 3D magnetic flux path, which results in a constant magnetic potential difference between the stator and rotor of the vernier machine. Hence, by evaluating the airgap field, the permeance distribution can be obtained according to (2). The homopolar field is clearly shown

in Fig. 5. Fig. 6 gives the comparison of permeance waveforms obtained from the proposed electrostatic FEA and 3D electromagnetic FEA. It can be seen that the waveforms match well. Therefore, the duality and reasonability of the proposed electrostatic FEA method for calculating airgap permeance has been verified.

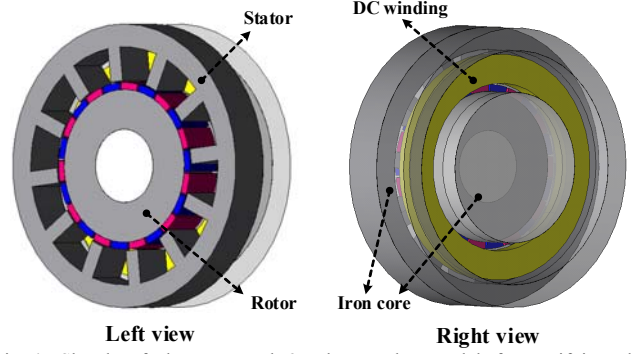


Fig. 4. Sketch of the proposed 3D homopolar model for verifying the permeance calculation.

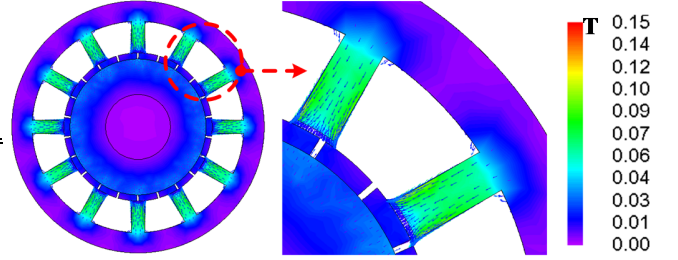


Fig. 5. Cross-section view of the magnetic field of the proposed 3D homopolar FEA model.

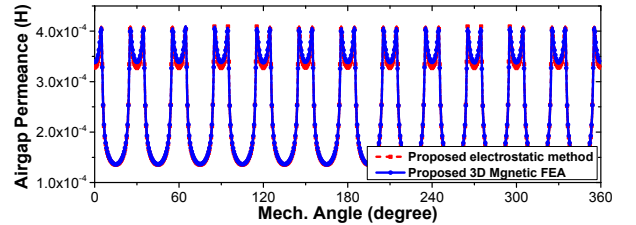


Fig. 6. Comparison of permeance waveforms obtained from the proposed electrostatic FEA and 3D electromagnetic FEA.

V. CONCLUSION

In this paper, a novel permeance calculation method based on 2D electrostatic FEA has been proposed. The effectiveness and accuracy of this method has been validated on a vernier PM machine. A 3D electromagnetic FEA for calculating the airgap permeance is also conducted, which has further verified the reasonability of the proposed method.

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