Air-gap Magnetic Field Analysis of Wind Generator with PM Embedded Salient Poles by Analytical and Finite Element Combination Technique

Yujing Guo, Heyun Lin*, Yunkai Huang, Shuhua Fang, Hui Yang, Kang Wang
Engineering Research Center for Motion Control of Ministry of Education, Southeast University, Nanjing 210096, China
*hyling@seu.edu.cn

***Abstract*—A combination technique of analytical method and finite element method (FEM) is proposed for predicting air-gap magnetic field distribution of a permanent magnet embedded salient pole wind generator (PMESPWG). By the combination technique, the calculation of magnetic field distributions when the stator and rotor are at different relative positions becomes much faster than that only by FEM. Based on the magnetic field distributions, the cogging torques are predicted and verified by FEM. The relationship between cogging torque and design parameters are further investigated. The proposed combination technique supplies an efficient and accurate prediction method for the magnetic field distribution of large electrical machines with complex PM pole structure.**

***Index Terms*—embedded salient pole, finite element method, wind generator**

I. INTRODUCTION

Permanent magnet embedded salient pole wind generator (PMESPWG) is a potential choice for offshore wind power generation because of the advantages of protection for PM and good heat dissipation [1]. For the magnetic saturation and the flux leakage in and between salient poles of PMESPWG, the analytical method cannot be directly applied in this kind of machine. Finite element method (FEM) can precisely obtain the magnetic field distribution of this kind of machine; however it is time consuming especially for large electrical machines. In [2], the combination of analytical method and FEM technique is applied in the magnetic field analysis of interior PM motors, but the accuracy of the calculation results is relatively poor due to the neglect of the circumferential relative permance effect.

This paper proposes an efficient combination technique of analytical method and FEM to analyze the air-gap magnetic field of PMESPWG. The radial and circumferential flux densities on the inner surface of stator when the stator is assumed to be slot-less are first calculated by FEM. And then they are modulated by the relative permeance for taking the slotting effect into account [3], [4]. The modulated flux densities on the inner surface of stator are used as the boundary conditions to analyze the air gap magnetic field distributions when the stator and the rotor are at different relative positions. In this way, the prediction of magnet field distribution with slots becomes very efficient since the FEM analysis needs to be done only once. By applying the proposed combination technique, the air-gap magnetic field distribution of a 3MW PMESPWG is fast and precisely predicted. The cogging torque of the machine are subsequently calculated and optimized.

II. AIR-GAP MAGNETIC FIELD CALCULATION

The structure of the PMESPWG under investigation is schematically illustrated in Fig. 1. The inner radius of the stator is R_s and the outer radius of the rotor is R_r . The PMs embedded in the salient poles are rectangular and of parallel magnetization. Each pole, as an independent component, is installed in the rotor yoke. The ventilation channel between the adjacent salient poles can enhance the circulation of air to cool the rotor.

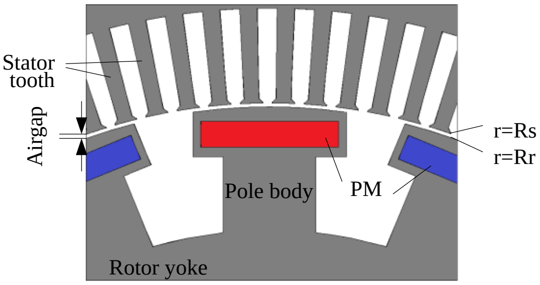
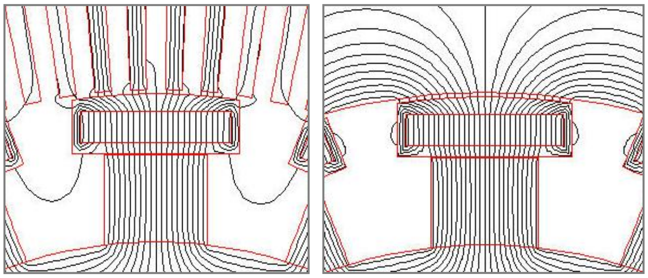


Fig. 1 Configuration of PMESP

The magnetic field distributions in the air gap when the stator is slotting and slot-less are markedly different, as shown in Fig. 2 (a) and (b).



(a) (b)

Fig. 2. Magnetic field distribution (a) slotting (b) slot-less

In order to take the magnetic saturation and the flux leakage in and between the salient poles into account, the radial flux densities B_{r1} and the circumferential flux densities $B_{\theta 1}$ at $r = R_s$ when the stator is assumed to be slot-less are first calculated by the FEM. By the fast Fourier transform, both of the two density distributions can be expressed as

$$B_{r1}(\theta,\theta_r)\big|_{r=R_s} = \sum_{n=1,2,3\ldots}^{\infty} B_{n1}^{r} cos(np(\theta-\theta_r)) \qquad (1)$$

$$B_{\theta 1}(\theta,\theta_r)\big|_{r=R_s} = \sum_{n=1,2,3\ldots}^{\infty} B_{n1}^{\theta} sin(np(\theta-\theta_r)) \qquad (2)$$

Considering the effect of the slots, the radial and circumferential flux density distributions at $r=R_s$ are modulated by the relative permeance method both at the radial and circumferential directions as follows

$$B_{r1} = B_{r1}\lambda_r + B_{\theta 1}\lambda_\theta \tag{3}$$

$$B_{\theta 1} = B_{\theta 1}\lambda_r - B_{r1}\lambda_\theta \tag{4}$$

where λ_r and λ_θ are the relative permeance in the radial and the circumferential directions respectively.

The modulated radial and circumferential flux density distributions at r=Rs are used as the boundary conditions in the solution of the Laplace's equation to yield the air-gap flux densities when the stator is slotting.

The analytical results of the radial and circumferential flux densities at the center of the air-gap are compared with the ones by FEM. As shown in Fig. 3, the analytical and the FEM results of the radial flux densities are in good agreement.

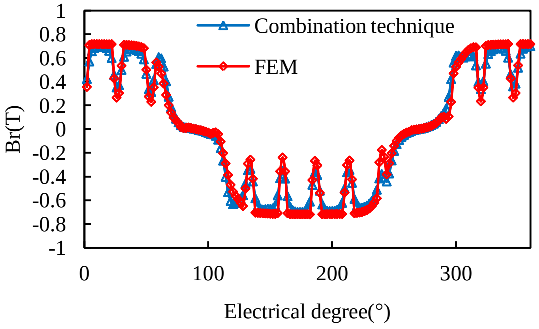


Fig. 3. Flux densities in the air-gap

III. COGGING TORQUE MINIMIZATION

The proposed combination technique is finally applied to minimize the cogging torque of a 3MW PMESPWG prototype with high efficiency. Table I gives the main structure parameters of the prototype. The cogging torque can be computed by applying the Maxwell stress tensor in the air gap [5]

$$T_c = (lr^2/\mu_0)\int_0^{2\pi} B_r(r,\theta)B_\theta(r,\theta)d\theta \tag{6}$$

where l is the axial length of the rotor, r is the radius of the air gap.

The analysis results by the combination technique are validated by FEM. The influence of design parameters on the cogging torque, such as pole arc coefficient, width of the side frame and height of upper core of the salient pole are respectively investigated.

The cogging torque waveforms with different pole arc coefficients are shown in Fig. 4. The variation of the peak cogging torque with pole arc coefficient is given in Fig. 5. As can be seen when the pole arc coefficient is equal to 0.68, 0.71, 0.75 or 0.79, the cogging torque is relatively small.

TABLE I

MAIN PARAMETERS OF PMESPWG

Parameters	Value	Parameters	Value
α_p	0.75	b_p	174 mm
p	8	h_p	54 mm
N_s	96	h_{pm}	28 mm
R_{si}	590 mm	w_{pm}	158 mm
R_r	562 mm	H_{pm}	889 kA/m
R_m	590 mm	μ_{pm}	1.09

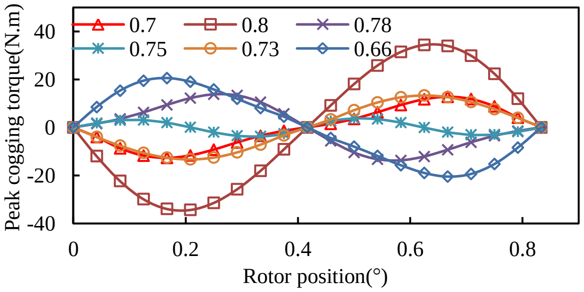


Fig. 4. Effect of pole arc coefficient on cogging torque waveform

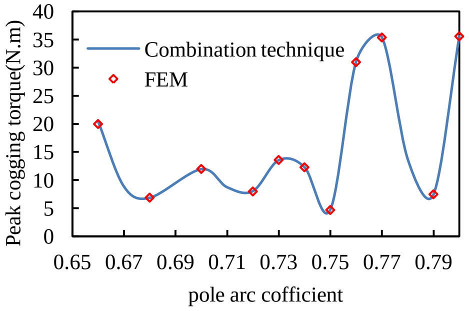


Fig. 5. Variation of peak cogging torque with pole arc coefficient

IV. CONCLUSION

The combination technique of analytical method and FEM , which takes both the radial and circumferential relative permeance into account, is proposed and successfully applied for predicting air-gap magnetic field distribution of a 3WM PMESPWG. By using the combination technique, the FEM is only used once, to obtain the air-gap magnetic field distribution when the stator and rotor at different relative positions. The cogging torque of the PMESPWG is calculated and optimized based on the combination technique. The combination technique supplies an efficient and accurate method for the analysis and optimization of this kind of machine with complex PM structure, especially for large capacity electrical generator.

REFERENCES

[1] Yujing Guo, Heyun Lin, Yi Feng, Jianhu Yan and Mingming Huang, "Design and analysis of a novel permanent magnet embedded salient pole for wind generator," in *Int. Conf. Electrical Machines and Systems*, Beijing, Aug. 2011.

[2] Hong-Seok Ko and Kwang-Joon Kim, "Characterization of noise and vibration sources in interior permanent-magnet brushless DC motors", *IEEE Trans.Magn.*, vol. 40, no. 6, pp. 3482–3489, Nov. 2004.

[3] D. Zarko, D. Ban, and T. A. Lipo, "Analytical calculation of magnetic field distribution in the slotted air gap of a surface permanent-magnet motor using complex relative air-gap permeance," *IEEE Trans. Magn.*, vol. 42, no. 7, pp. 1828–1837, Jul. 2006.

[4] D. Zarko, D. Ban, and T. A. Lipo, "Analytical solution for cogging torque in surface permanent-magnet motors using conformal mapping," *IEEE Trans. Magn.*, vol. 44, no. 1, pp. 52–65, Jan. 2008.

[5] L. J. Wu, Z. Q. Zhu, David A. Staton, Mircea Popescu and D. Hawkins, "Comparison of analytical models of cogging torque in surface-mounted PM machines," *IEEE Trans. Ind. Electron.*, vol. 59, no. 6, pp. 2414–2425, Jun. 2012.