

Study on a Correction Coefficient for 3D Axial Leakage Flux Considering Fringing Effects in Bar-type IPMSM

Do-Hyun Kim¹, Sung Gu Lee^{1†}

¹Department of Electrical Engineering, Dong-A University, Busan, 49315 South Korea, sunggu@dau.ac.kr

The Interior Permanent Magnet Synchronous Motor (IPMSM) offers advantages such as preventing magnet detaching without increasing the air gap length and utilizing additional torque through flux-weakening control, enabling a wide operating range. However, it also has drawbacks, including 2D leakage flux through the ribs that bypasses the stator coils and 3D axial leakage flux through the upper and lower rotor core air gaps, which are magnetically isolated by the saturated ribs and permanent magnets (PM). This study addresses the impact of 3D axial leakage flux, which has not been considered in previous research, by introducing a correction coefficient, formulated as a closed-form expression based on key design parameters, and incorporating it into the 2D Finite Element Analysis (FEA)

Index Terms—3D axial leakage magnetic flux, Correction coefficient, interior permanent magnet synchronous motor

I. INTRODUCTION

IPMSMs are widely employed in applications requiring a broad variable-speed operating range, such as electric vehicle traction motors and household washing machine motors. Previous research in bar-type IPMSM has primarily focused on leakage flux that originates from the N pole of a single embedded PM within the rotor core, passes through the rotor core ribs, and arrives at the S pole of an adjacent magnet. This flux path is confined to a 2D plane, allowing for analysis using 2D FEA. The 2D leakage flux passing through the ribs contributes to performance degradation; thus, the ribs are designed to minimize thickness in order to mitigate these effects. Consequently, the design process must account for both mechanical robustness and electromagnetic performance to achieve an optimal balance[1]-[2]. However, the 3D axial leakage flux considered in this study has not been addressed in previous research. Due to the 2D leakage flux, a magnetic potential difference arises between rotor core regions that are magnetically isolated by fully saturated ribs, as shown in Fig. 1. As a result, the 3D axial leakage flux follows a 3D path starting from a certain area of the rotor core, passing through the non-magnetic air regions above and below the rotor, then reaching another region of the rotor core.

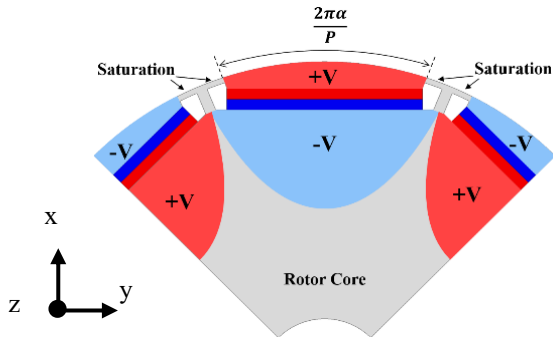


Fig. 1. Magnetic potential difference in rotor core in Bar-type IPMSM

In IPMSMs, this 3D axial leakage flux also degrades motor performance. Because the flux path is inherently 3D, accurately accounting for its effect requires 3D FEA. However, 3D FEA is significantly more time-consuming than 2D FEA, making it challenging to consider the 3D axial

leakage flux during the early design stage, where 2D FEA is predominantly used. In this study, a Correction coefficient is proposed to incorporate the performance degradation caused by 3D axial leakage flux into 2D FEA.

II. PERMEANCE MODELING

A. 2D permeance modeling

To design a magnetic equivalent circuit (MEC), the permeance must be calculated. The air gap permeance P_g and the PM permeance P_m are expressed by (1) and (2), considering the geometric structure in the XY-plane and the stack length in the Z-direction.

$$P_g = \frac{2\mu_0 \alpha \pi L_s}{P \ln\left(1 + \frac{g}{R_r}\right)} \quad (1)$$

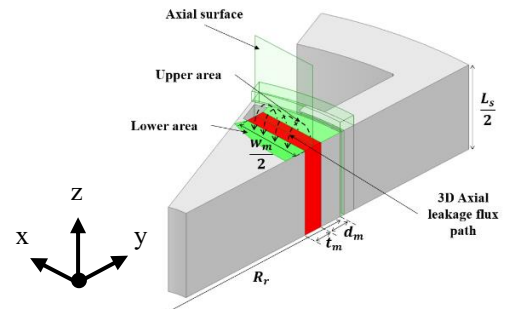
$$P_m = \frac{\mu_0 \mu_r w_m L_s}{2t_m} \quad (2)$$

B. 3D permeance modeling

The minimal symmetric model is shown in Fig. 2. The 3D axial leakage flux follows a path beginning from the upper area (pole-piece) of the rotor core, and arriving at lower area (inner rotor core) of the rotor core. If leakage flux is assumed to occur over the entire pole-piece, the axial permeance, determined by the geometric structure, can be expressed as shown in (3).

$$P_{axial} = \int_0^{\frac{w_m}{2}} \frac{2\mu_0}{\pi} \frac{\sqrt{(R_r)^2 - x^2} - (R_r - d_m)}{\sqrt{(R_r)^2 - x^2} - \left(R_r - d_m - \frac{t_m}{2}\right)} dx \quad (3)$$

The numerator of P_{axial} is defined by a differential integration in the x-direction—using the rotor circle equation and the region divided by the magnet—to compute the total area of the x-direction measured from the center of the



permanent magnet.

Fig. 2. Path of 3D axial leakage flux

P_{axial} is the permeance without considering fringing effects. In particular, the axial permeance through air considers fringing effects that occur due to the non-magnetic gap

C. Back electromotive force for 2D & 3D

By comparing the linkage flux in the 2D and 3D MEC, the Correction coefficient is obtained. This coefficient is applied by multiplying the residual magnetic flux density of the PM during 2D FEA. The accuracy of the proposed coefficient is verified by comparing the no-load back electromotive force (EMF) obtained from a 2D FEA without the coefficient, 2D FEA with the coefficient, and 3D FEA. [3]

$$\beta = \frac{\lambda_{3D \text{ link}}}{\lambda_{2D \text{ link}}} = \frac{\frac{(\phi_m - \phi_r)(P_g + 4P_{axial})}{P_g + 2P_m + 4P_{axial}}}{\frac{(\phi_m - \phi_r)P_g}{P_g + 2P_m}} = \frac{(P_g + 4P_{axial})(P_g + 2P_m)}{(P_g + 2P_m + 4P_{axial})P_g} \quad (4)$$

The back EMF is proportional to the linkage flux. The calculated β , through (4), is a Correction coefficient and is applied by multiplying it with the residual magnetic flux density.

III. CONSIDERATION OF FRINGING EFFECTS

As shown in Fig. 3(a), the ideal flux path is assumed circular for ease of calculation. However, the real 3D axial leakage flux in IPMSMs, as shown in Fig. 4(a), exhibits fringing effects and should therefore be considered as following an

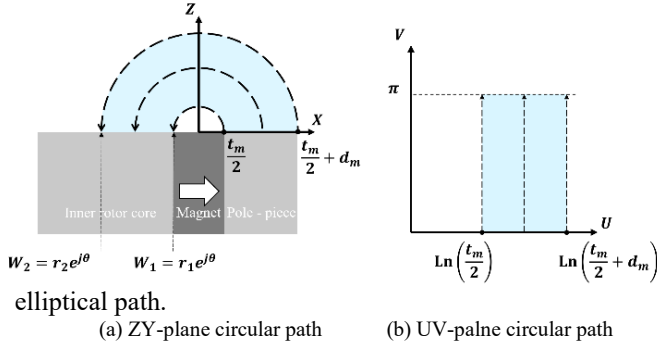


Fig. 3. Ideal Axial Leakage Path

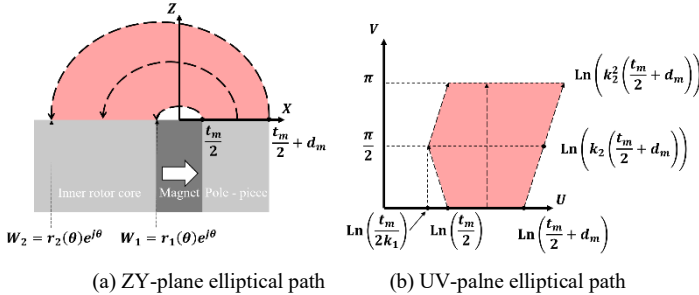


Fig. 4. real Axial Leakage Path

Since such fringing effects cannot be directly accounted for in the integration process used to calculate P_{axial} , conformal mapping is employed to correct for this discrepancy. k_1 and k_2 are determined by different combinations of d_m and t_m , and can be obtained through a comparison between FEA and

MEC[4]. As shown in Fig. 4(b), Where $\mathcal{R}_1$ is the reluctance of a trapezoidal section in Region 1,

$$\mathcal{R}_1 = \frac{\ln\left(\frac{\ln(k_1 k_2) + \ln\left(1 + \frac{2d_m}{t_m}\right)}{\ln\left(1 + \frac{2d_m}{t_m}\right)}\right)}{\frac{\mu_0 w_m}{\pi} \ln(k_1 k_2)} = \frac{\pi X_1}{\mu_0 w_m \ln(k_1 k_2)} \quad (5)$$

$$\mathcal{R}_2 = \frac{\ln\left(\frac{2 \ln(k_1) + 2 \ln\left(\frac{k_2}{k_1}\right) + \ln\left(1 + \frac{2d_m}{t_m}\right)}{2 \ln(k_1) + \ln\left(\frac{k_2}{k_1}\right) + \ln\left(1 + \frac{2d_m}{t_m}\right)}\right)}{\frac{\mu_0 w_m}{\pi} \ln\left(\frac{k_2}{k_1}\right)} = \frac{\pi X_2}{\mu_0 w_m \ln\left(\frac{k_2}{k_1}\right)} \quad (6)$$

where $\mathcal{R}_2$ is the reluctance of a parallelogram section in Region 2.

$$P_{real} = \frac{1}{\mathcal{R}_1 + \mathcal{R}_2} = \frac{\mu_0 w_m}{\pi} \frac{\ln\left(\frac{k_2}{k_1}\right) X_1 + \ln(k_1 k_2) X_2}{\ln(k_1 k_2) \ln\left(\frac{k_2}{k_1}\right)} \quad (7)$$

$$P_{ideal} = \frac{\mu_0 w_m}{\pi} \ln\left(1 + \frac{2d_m}{t_m}\right) \quad (8)$$

Where X_1, X_2 are simplified forms of the complex equation in the numerator. By comparing the ideal circular path with the real elliptical path, the correction is determined using (5)-(7).

$$k_{frg} = \frac{P_{real}}{P_{ideal}} = \frac{2 \ln(k_1 k_2) \ln\left(\frac{k_2}{k_1}\right)}{\left(\ln\left(\frac{k_2}{k_1}\right) X_1 + \ln(k_1 k_2) X_2\right) \ln\left(1 + \frac{2d_m}{t_m}\right)} \quad (9)$$

By multiplying the proposed coefficient k_{frg} with (3), the improved P_{axial} , which accounts for the fringing effects, can be used to obtain an accurate correction coefficient in (4). The simulation results obtained by applying the proposed correction coefficient β to the residual magnetic flux density from the 2D FEA demonstrate that the performance degradation neglected in conventional 2D FEA can be accurately reflected.

TABLE I
COMPARISON OF BACK EMF ACCORDING TO GEOMETRIC PARAMETERS

t_m [mm]	d_m [mm]	Conventional 3D EMF [V _{rms}]	Conventional 2D EMF [V _{rms}]	Proposed 2D EMF [V _{rms}]
2	2.5	33.96	34.87 (2.68%)	33.33 (1.86%)
2.5	3	34.44	35.50 (3.08%)	33.94 (1.45%)
3	3.5	34.19	35.38 (3.47%)	33.84 (1.03%)

TABLE II
NOMENCLATURE OF MAIN PARAMETERS

Parameter	Symbol	Quantity
Number of poles	P	8
Ratio of pole pitch	α	0.8054
Stack length	L_s	25mm
Diameter of rotor	R_r	30mm
Mechanical air gap	g	0.6mm
Width of magnet	w_m	18mm
Thick of magnet	t_m	2mm, 2.5mm, 3mm
Depth of magnet from rotor diameter	d_m	2.5mm, 3mm, 3.5mm

REFERENCES

- [1] H. -K. Lim, B. -K. Song, S. -I. Kim and J. -P. Hong, "A study on the relation between rotor rib and maximum power of IPMSM in flux weakening region", 2010 International Conference on Electrical Machines and Systems, Incheon, Korea (South), 2010, pp. 1222-1225.
- [2] C. -M. Kim, H. -S. Shin, C. -H. Lee and K. -C. Kim, "A Study on Operation Characteristics According to Rib Thickness for Each Layer of Double V-type IPMSM", 2022 25th International Conference on

Electrical Machines and Systems (ICEMS), Chiang Mai, Thailand, 2022, pp. 1-5, doi: 10.1109/ICEMS56177.2022.9983343.

- [3] S. G. Lee, J. Bae and W. -H. Kim, "Study on the Axial Leakage Magnetic Flux in a Spoke Type Permanent Magnet Synchronous Motor," in *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 5881-5887, Nov.-Dec. 2019, doi: 10.1109/TIA.2019.2939743.
- [4] S. G. Lee, J. N. Bae and W. -H. Kim, "Study on the Axial Leakage Magnetic Flux in a Spoke Type Permanent Magnet Synchronous Motor", *IEEE Trans. on Industry Applications*, vol. 55, no. 6, Nov.-Dec. 2019, pp. 5881-5887