A Novel 2-Dimensional Analysis Method considering Axial Flux Leakage in Spoke-Type Permanent Magnet Machines

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This paper presents a novel 2-dimensional (2-D) analysis method for spoke-type permanent magnet (PM) machine. With an accuracy limitation of conventional 2-D analysis method due to the axial flux leakage generated largely around PMs, a novel conversion factor through detailed analysis of flux path is proposed. The virtual residual magnetic flux density of PM for the improved 2-D analysis are determined using the factor and the accuracy and usefulness of the proposed method is confirmed through the 3-D numerical analysis.

***Index Terms*—2-D conversion analysis, Axial Flux leakage, Residual magnetic flux density, Spoke-type permanent magnet machine.**

I. INTRODUCTION

The spoke-type permanent magnet (PM) machine has the advantage that the magnetic flux from the PM can be concentrated because the magnetization direction of the PM is designed to be symmetrical as shown in Fig. 1. That is, since the PM is embedded in both ends of the rotor pole and the magnetic pole is formed on the surface of the rotor core between the PMs, It is possible to increase the air gap magnetic flux density by increasing the cross-sectional area of the PM to the magnetic pole surface even if the mechanical specification of the rotor is constant. Therefore, the spoke-type PM machine can obtain the highest level of magnetic flux amount in the same PM volume, so that the price competitiveness is excellent among various PM machines [1]. For example, spoke machines utilizing low-cost ferrite PMs may replace surface-mounted machines with expensive rare-earth PMs.

The effective magnetic flux concentration is a distinct advantage in the spoke-type PM machine, however, there is also a disadvantage that leakage magnetic flux due to the surface area of a relatively large PM is also generated [2]. Fig. 2 shows axial magnetic flux density distributions of spoke machine through 3-dimensional (3-D) analysis. The magnetic flux is leaking around all of the rotor core in which the PM is inserted as well as the air gap. The amount of leakage flux tends to increase as the width of the PM is short and the length is long. The back electromotive force (EMF) by the 2 and 3-D analysis of the spoke machine shows a difference of about 9% as shown in this figure. EMF decrease is directly related to the increase of input current and copper loss due to the reduction of the torque constant. Therefore, in designing the spoke-type PM machine, it is necessary to consider the axial leakage magnetic flux through the 3-D analysis. However, the 3-D numerical analysis in the initial design stage can be inefficient and time-consuming as a modeling and solving process. To address this problem, we propose a novel 2-D analysis method that considers 3-D flux leakage effectively.

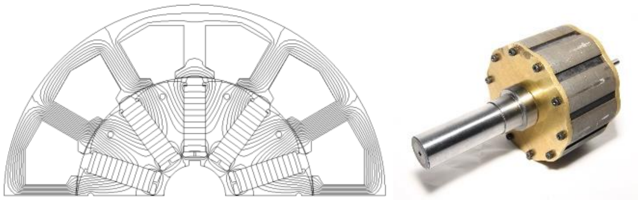

Fig. 1. The magnetic flux line of the spoke-type PM machine (left) and prototype of rotor (right).

II. PROPOSED ANALYSIS METHOD

This paper presents the redefinition of the residual magnetic flux density (remanence) of PMs for 2-D analysis based on the air gap flux density calculated from 2 and 3-D models. In this process, a conversion factor expressed by the shape dimension and permeability of the model is proposed and its usefulness is confirmed. The proposed method and procedure are as follows. First, 2-D magnetic equivalent circuit (MEC) model is constructed to calculate the air gap flux density. The MEC consists of each reluctance corresponding to the stator and rotor core, air gap, and leakage with the remanence of the PM as the current source. Fig. 3 shows the flux path and MEC model of a simplified spoke-type PM machine. The magnetic flux generated from the PM circulates through the rotor core, air gap, and stator core in order, some magnetic flux leaks to the air gap and back side of rotor core. The air gap flux density is calculated as follows.

$$B_{g\_2D} = k_{2D} B_r \tag{1}$$

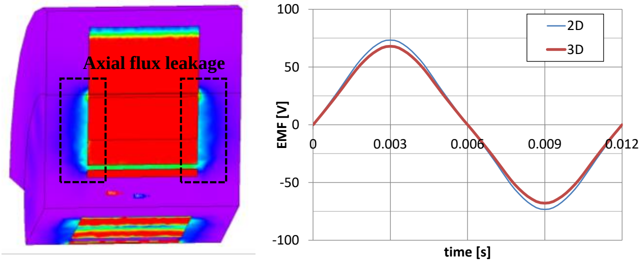

Fig. 2. The axial flux leakage of spoke-type PM machine (left) and the calculated back EMF form 2-D and 3-D FEA (right).

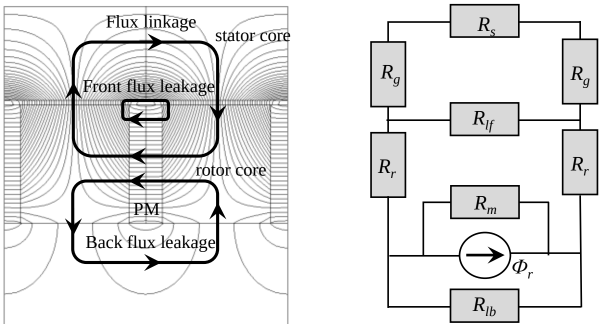

Fig. 3. The simplified 2-D analysis model for the spoke machine (left) and the corresponding MEC model (right).

where B_r is remanece of PM and

$$k_{2D} = \frac{h_f \pi}{4g(2+\ln(1+\frac{h_f}{h_m})+\ln(1+\frac{\pi g}{h_m})+\frac{h_f \pi}{4g}+\frac{\mu_r \omega_m \pi}{h_m}}. \quad (2)$$

The calculated air gap flux density agrees well with the 2-D numerical analysis results as shown in Fig. 4. Next, the 3-D MEC model which adds the reluctance corresponding to the axial flux leakage that cannot be considered in 2-D model is constructed as shown in Fig. 5. The air gap flux density using the 3-D circuit model is calculated as (3), and compared with the numerical analysis results in Fig. 6.

$$B_{g\_3D} = k_{3D} B_r \quad (3)$$

where

$$k_{3D} = \frac{h_f \pi}{4g(2+\ln(1+\frac{h_f}{h_m})+\ln(1+\frac{\pi g}{h_m})+\frac{h_f \pi}{4g}+\frac{\mu_r \omega_m \pi}{h_m}+\frac{\omega_m}{L}(2\ln(1+\frac{h_f}{h_m})+4)+\frac{h_f \pi}{2L}}. \quad (4)$$

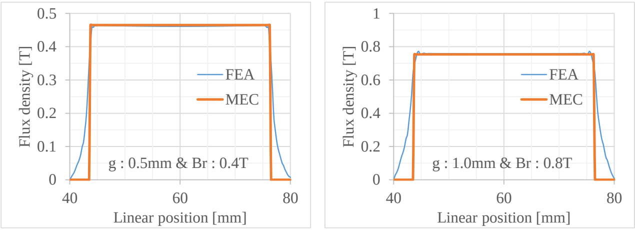

Fig. 4. Comparison of air gap flux density with respect to the air gap length and remanence of PM using 2-D FEA and MEC model.

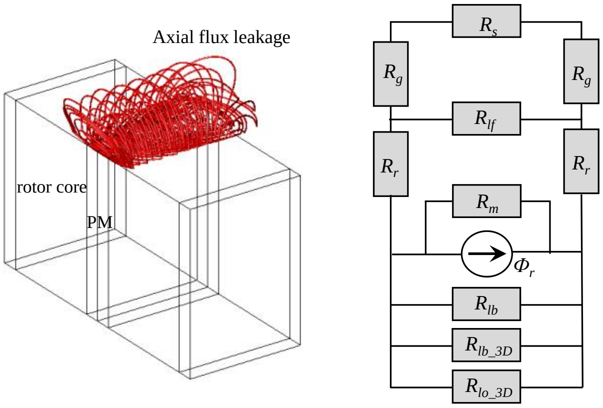

Fig. 5. Axial flux leakage generated along the PMs (left) and 3-D MEC model considering the flux leakage (right).

B_{g_3D} can be expressed by (1), (3), and the virtual remanence as follows.

$$B_{g\_3D} = k_{2D} B_r^{'}. \quad (5)$$

By (3) and (5)

$$k_{3D} B_r = k_{2D} B_r^{'} \quad (6)$$

and the virtual remanence of PM for 2-D analysis can be expressed by

$$B_r^{'} = C B_r \quad (7)$$

where the conversion factor C is

$$C = k_{3D} / k_{2D}. \quad (8)$$

Fig. 7 shows the air gap flux density calculated using the remanence determined by the proposed analysis method. The 2-D analysis results agree well with 3D one with various change of the air gap length and remanence of PM.

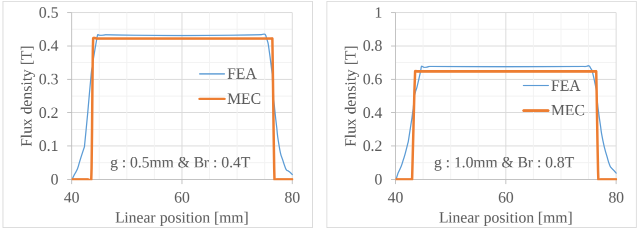

Fig. 6. Comparison of air gap flux density with respect to the air gap length and remanence of PM using 3-D FEA and MEC model.

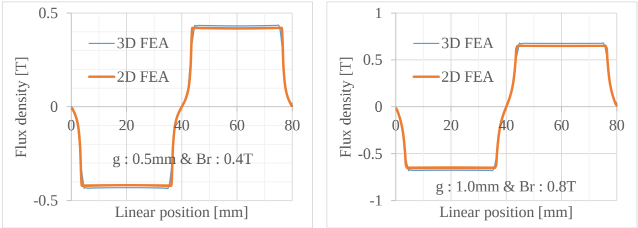

Fig. 7. Comparison of air gap flux density with respect to the air gap length and remanence of PM using the proposed 2-D conversion method.

III. CONCLUSION

In this paper, a novel 2-D analysis method is proposed to effectively consider the 3-D flux leakage of a spoke-type PM machine. The electromagnetic characteristics of the machine are analyzed easily and quickly by only using the 2-D analysis thanks to the effective remanence of PM. In a following paper, we will present detailed analysis methods and the accuracy and usefulness of the proposed method will be verified through practical case studies.

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