A Novel Approach for Axial End Leakage Flux of Spoke-type Interior Permanent Magnet Motors Using Magnetic Equivalent Circuit

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In the case of a spoke-type interior permanent magnet (IPM) motors which have a relatively short stack length as compared with the outer stator diameter, the outputs such as back electro-motive force (EMF) and torque is less than expected by using 2D finite-element analysis (FEA) due to the axial end leakage. In this paper, the magnetic equivalent circuit for spoke-type IPM motors reflecting the axial end leakage flux is proposed to exactly calculate the outputs such as back EMF and torque. The airgap permeance reflects the uneven airgap shape such as eccentricity and chamfer by dividing the airgap into many differential elements and calculating each differential permeance. Results from the magnetic equivalent circuit is compared with the results from 2D, 3D FEA and measurement. As a result of comparison, the acceptable results are achieved and the computational time is saved dramatically.

***Index Terms*—Axial end leakage, Magnetic equivalent circuit, Spoke-type IPM motors, Uneven airgap**

I. Introduction

RECENTLY, interior permanent magnet (IPM) motors without rare-earth permanent magnet (PM) have been actively researched due to the problems of the rare-earth such as the environmental destruction during mining and the significant price fluctuations in international markets. In this paper, spoke-type IPM motors which do not use rare-earth PM is used.

Many applications such as in-wheel direct drive systems and washing machines require short stack length and compact design to be placed in the narrow space. However, such flat machines, so-called pancake type machines, bring about higher axial end leakage than the pencil type machines. In this reason, the experimental measurement is often less than the 2D finite-element analysis (FEA) in design.

FEA can be used to obtain the exact value, but it has the disadvantage of time-consuming and troublesome pre-processing. Thus, magnetic equivalent circuit analysis is often used, since it can provide acceptable accuracy with little effort and save computational time. However, there are few studied on magnetic equivalent circuit for spoke-type IPM motors reflecting uneven airgap such as eccentricity or chamfer.

Thus, in this paper, a novel approach for axial end leakage flux of spoke-type IPM motors using magnetic equivalent circuit reflecting uneven airgap is proposed and then results predicted from the magnetic equivalent circuit is compared with those derived from 2D and 3D FEA and measurements for two pancake type motors.

II. Magnetic Equivalent Circuit Modeling

The Fig. 1. shows a magnetic equivalent circuit per pole in consideration of the periodicity. Elements of the magnetic equivalent circuit consist of PM, leakage bypass, axial end leakage, airgap and rotor slot opening. The core permeability excluding leakage bypass is assumed to be infinite. The rotor fringing flux is reflected by dividing the rotor slot opening finite. The effect of stator is reflected by using relative specific permeance.

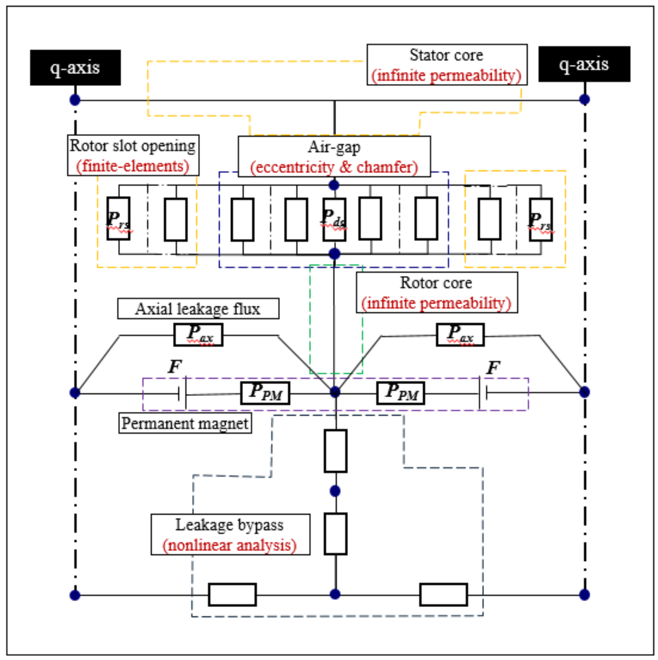

Fig. 1. Magnetic equivalent circuit for spoke-type IPM motors.

A. Axial end leakage permeance

The axial end leakage flux means to flux that leaks in the axial direction without passing through the airgap. For a pancake type motors which have a short stack length, since the ratio of the air gap cross-sectional area to the axial directional cross-sectional area are relatively smaller than the pencil type motor, the influence of axial end leakage flux is relatively increased. So, the exact calculation of the axial end leakage permeance is required to obtain the exact results from the magnetic equivalent circuit.

The axial end leakage flux paths are assumed to be semicircular, as shown in Fig. 2. The axial end leakage permeance P_{ax} consists of two components, i.e.,

$$P_{ax} = 2\left(P_{ax1} + P_{ax2}\right) \qquad (1)$$

$$P_{ax1} = 0.26\mu_0 t_{PM} \quad (2)$$

$$P_{ax2} = \frac{\mu_0 L_{stk} \ln\left(\frac{\pi D}{t_{PM}}\right)}{\pi} \quad (3)$$

Where μ_0, t_{PM}, L_{stk} and D is the vacuum permeability, the PM thickness, the stack length and the radius of the axial end leakage flux, respectively. The P_{ax1} is the permeance of the axial end leakage path from edge to edge of the rotor core. The P_{ax2} is the permeance of the axial end leakage path from face to face of the rotor core. The calculated axial end leakage permeance is connected in parallel with the PM permeance.

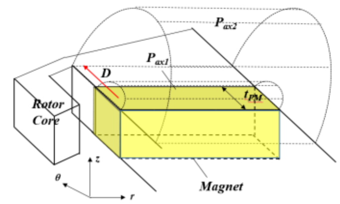

Fig. 2. Axial end leakage flux paths.

B. Airgap division

The airgap needs to be divided into many differential elements with the same cross-sectional area to account for the rotor eccentricity or chamfer. Each differential permeances can be calculated by substituting each airgap length. The airgap length is calculated by the relationship between the equations of the circle in which stator and rotor are transformed.

III. Predicted and FEA Results

For two pancake type motors, back EMF and torque from the foregoing developed magnetic equivalent circuit are compared with 2D and 3D FEA results. Two separated models are 8-Pole, 12-Slot and 14-Pole, 18-Slot, respectively, whose stator diameter and stack length are given in Table I.

Fig. 3. shows the comparison result in the model 1 with chamfer. The Analytical Method(ANA) is calculated by using the foregoing developed magnetic equivalent circuit. The back EMF is calculated under the load condition at a speed of 1000 (rpm) and the rms value of input current is 2.121 (A_{rms}), the current phase angle is 0º

Fig. 4. shows the comparison result in the model 2. The back EMF is calculated under the load condition at a speed of 279 (rpm) and the rms value of input current is 16.7 (A_{rms}), the current phase angle is 0º

The error between results from the proposed magnetic equivalent circuit and the 3D FEA is within 3% in both models. Experiments on model 1 are in progress. The average computational time by using the magnetic equivalent circuit and 3D FEA is 30 (sec.) and 50 (min.), respectively. Thus, using the proposed magnetic equivalent circuit, the acceptable results such as back EMF and torque can be achieved and saved the computational time dramatically.

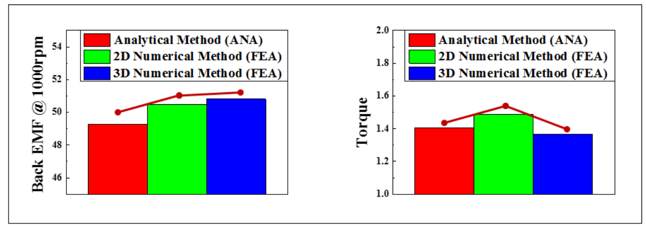

Fig. 3. Comparison of the back EMF and the torque in the model 1.

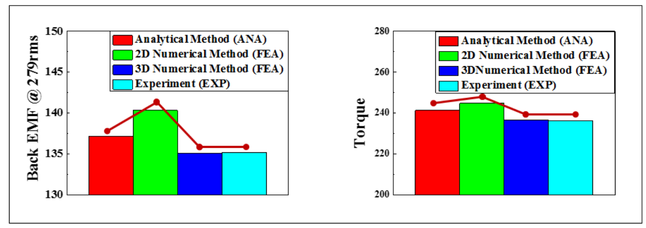

Fig. 4. Comparison of the back EMF and the torque in the model 2.

TABLE I
Dimensions of Two Models

Dimension	Value	Unit
Stator diameter of model 1	90	(mm)
Stator diameter of model 2	307	(mm)
Stack length of model 1	17	(mm)
Stack length of model 2	200	(mm)

IV. Conclusion

In this paper, a novel approach for axial end leakage flux of spoke-type IPM motors by using the magnetic equivalent circuit is proposed. The magnetic equivalent circuit has been developed to obtain back EMF and torque even with uneven airgap. Results from the magnetic equivalent circuit are compared with the 2D and 3D FEA results for two models. As a result of comparison, by using the magnetic equivalent circuit, the acceptable results can be obtained and save the computational time dramatically.

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