Novel Approach for Torque Calculation of Surface-Mounted PMSM considering Axial End Leakage Flux

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This paper proposes a novel approach for calculation of axial end leakage flux of the surface-mounted PMSMs. In order to calculate the axial end leakage flux using the 2-D FEA, the leakage magnetic flux in the axial direction is reflected to the 2-dimensional model by adding a factor to the permeability of the slot. The factor applied to the slot permeability is calculated by the equivalent magnetic circuit (EMC) method. At this time, the permeability factor is calculated by considering the main leakage path in the slot and the leakage path in the axial direction. The effectiveness of the proposed method is verified by comparing the results of the proposed method with the experimental results and the conventional 2-D FEA results and 3-D FEA results.

***Index Terms*—Axial end leakage flux, Equivalent magnetic circuit, Finite element analysis, Permeance**

I. Introduction

PERMANENT magnet synchronous machines (PMSMs) have been used in a variety of automotive applications in order to exhibit high torque per unit volume. Many applications for automotive chassis systems and in-wheel direct drive systems require their flat and compact designs so that they can be placed in the limited space. Such flat machines, however, bring about higher axial end leakage flux and higher fringing flux than the thick machines when exposed to a time varying magnetic field. That eventually makes it difficult to estimate the performance of the thin PMSMs using 2-D finite element analysis (FEA). As a result, when they are manufactured and tested to validate their performance, there are significant error between 2-D FEA results and experimental data. Hence, an appropriate approach such as 3-D FEA is required to reflect the magnetic phenomena that appears end area of stator and rotor and then predict the electromagnetic characteristics accurately.

Although various academic researchers have mentioned the electromagnetic characteristics of the PMSMs, only few papers have discussed the quantitative understanding of the axial end leakage flux [1]-[2]. Potgieter *et al*. mainly discussed the influence of the end-winding inductance and the end-flux fringing effects in PMs on the performance, but there was a limitation in terms of some assumptions [3]. Chen *et al.* dealt with the lumped parameter magnetic circuit (LPMC) of the flux-switching PM machine but it cannot be out of bounds for the lumped parameter method [4].

This paper proposes a novel approach for calculation of axial end leakage flux of the surface-mounted PMSMs. In order to calculate the permeability factor, the permeance of the main leakage and the axial leakages and are assumed. Using the Equation, which is the sum of all the permeances considering both ends, the permeability factor to be applied to the two-dimensional model is calculated. Finally, by applying the calculated value to the 2-D FEA and performing the finite element analysis, the axial leakage magnetic flux can be reflected in the 2-D FEA. To verify the reliability of the proposed method, we compared the coupled 2D-FEA and EMC method with the conventional 2-D FEA results, 3-D FEA results and the experimental results.

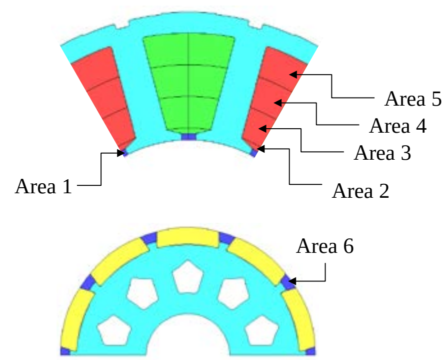

Fig. 1. Studied model and area for calculation of permeability factor

II. Studied Model

The models consist of relatively smaller rotor diameter compared to out diameter of stator core for lower inertia and fast response. The model studied was designed for a 10 pole, and 12 slots with low torque ripple despite high magnetic saturation of stator teeth and yoke for compact size. In the case of a motor with a high magnetic flux density and a small rotor outer diameter, the leakage flux between slots at the tooth tip is considerably large. In addition, the leakage magnetic flux at the end portion in the motor axial direction cannot be ignored. Therefore, as described above, 2D FEA modeling is performed as shown in Fig. 1 so that axial flux leakage can be considered by applying permeability factor to slots. The slot permeability factor was obtained by dividing the stator slot into five areas from Area 1 to Area 5. On the other hand, since the axial air leakage flux cannot be neglected in the air space between the poles of the rotor, the magnetic permeability factor in Area 6 is also calculated.

III. COUPLED 2D FEA AND EQUIVALENT MAGNETIC CIRCUIT METHOD

In order to calculate the permeability factor, the permeance P_{mn} of the main leakage and the axial leakages P_{sen} and P_{ten} are assumed as shown in Fig 2. W_{sn} is the width of the airspace in one area, H_{sn} is the length of the airspace, and d is the distance between stator teeth or permanent magnet centers.

In this paper, equations of permeance using the EMC method are referred to [4]. The permeance of the main leakage magnetic circuit, which can be analyzed in the two-dimensional FEA, is obtained as shown in equation 1. P_{sn} represents the permeance to the axial leak only in the air region and is given by equation 2. P_{ten} in equation 3 represents the permeance to the magnetic flux leaking axially between the core regions or the magnet region. Using the equation 4, which is the sum of all the permeances considering both ends, the permeability factor to be applied to the two-dimensional model is calculated and the equation 5 is calculated. Finally, by applying the calculated u_{rf} value to the 2D FEA and performing the finite element analysis, the axial leakage magnetic flux can be reflected in the 2D FEA. In the formula, the subscript n means the n-th region, and R_{ao-n} and R_{ai-n} mean the outer and inner diameters of the nth air region, respectively.

$$P_{mn} = \mu_0 \cdot \frac{H_{sn} \cdot L_{stk}}{W_{sn}} \tag{1}$$

$$P_{sen} = 0.264\mu_0 \times H_{sn} \tag{2}$$

$$P_{ten} = \frac{H_{sn}}{\pi} \cdot \frac{\mu_0 \cdot \ln\left(1 + \frac{\pi(R_{ao\cdot n} + R_{ai\cdot n})}{(0.5 \times N_{slot})} - W_{sn}\right)}{W_{sn}} \tag{3}$$

$$P_{n\_Total} = 2\left(P_{sen} + P_{ten}\right) + P_{mn} \tag{4}$$

$$\mu_{rf} = \frac{P_{n\_Total}}{P_{n\_mn}} \tag{5}$$

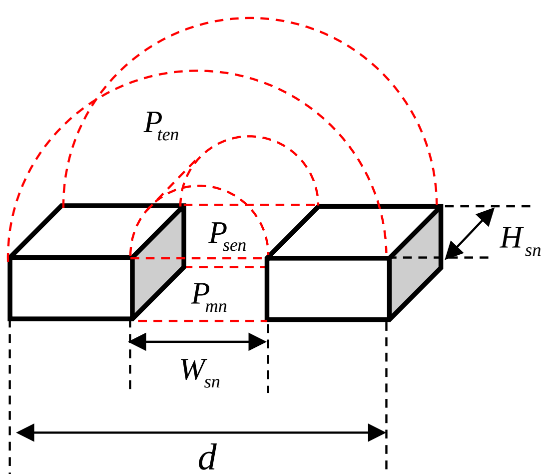

Fig. 2. Permeance of main and axial leakage flux path.

TABLE I
COMPARISON OF ANALYSIS AND EXPERIMENTAL RESULTS FOR VERIFICATION.

Line current [Arms]	Classification	2-D FEA	3-D FEA	Proposed method	Experimental results
65	Torque [Nm]	1.90	1.74	1.69	1.63
35		1.12	1.1	1.08	1.04
15		0.50	0.49	0.49	0.44
0	Back EMF [Vrms]	2.0	2.0	2.02	1.98

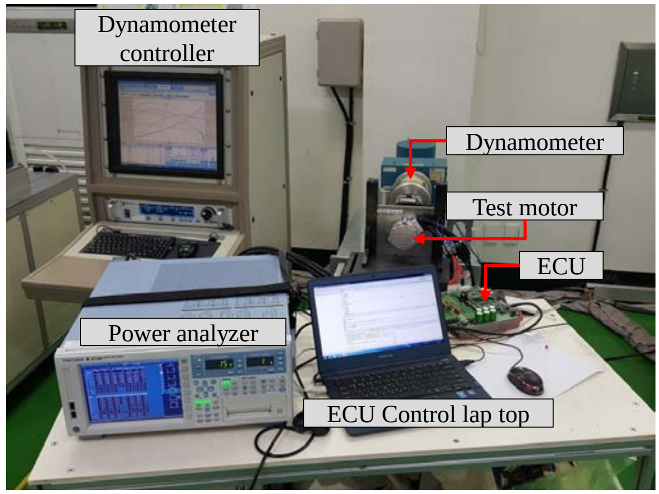

Fig. 3. Test set-up.

IV. EXPERIMENTAL VERIFICATION AND CONCLUSION

In order to verify the reliability of the proposed method, we compared the coupled 2D-FEA and EMC method with the conventional 2D FEA results and the experimental results which is obtained test set-up shown in Fig. 3. In addition, the validity of the analytical results is verified by comparing the 3D FEA results that can consider the three - dimensional leakage flux. No load back EMF and torque per current are compared in Table I. The no load back EMF values were similar in all the analysis methods, but the experimental results and the analysis results differ from each other as the current increases. The conventional 2D analysis results show an error of 14.2% when applying the maximum current as compared with the experimental results, whereas the proposed method shows an error of 3.3%. In the full paper, detailed background, calculation process and results will be covered.

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