Characteristics Analysis of SPMSM Using 2-D Finite-Element Analysis Considering Axial Leakage Flux

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In this paper, the characteristics analysis of the surface-mounted permanent-magnet synchronous motor is carried out using the method of reflecting the axial leakage magnetic flux into the 2-D finite-element analysis (2-D FEA), and the result is discussed. For the method of projecting the axial leakage flux on the 2-D plane, the permeance coefficient was introduced. By using the proposed method, the parameters such as d- and q-axes inductance and linkage flux for d- and q-axes equivalent circuit analysis were calculated, and the characteristics analysis was performed. In order to verify the effectiveness of the proposed 2-D FEA, a speed versus torque experiment was performed and compared with the analysis results.

Index Terms— **Axial leakage flux, d- and q-axes equivalent circuit analysis (ECA), d- and q-axis inductance, finite-element analysis (FEA), linkage flux, permeance, permeance factor.**

I. Introduction

GENERALLY, 2-D finite-element analysis (2-D FEA) is used instead of 3-D FEA (3-D FEA) for the surface-mounted permanent-magnet synchronous motor (SPMSM) which does not have a complicated shape. Due to the development of various numerical analysis techniques and computer technology, there is no problem in using 2-D FEA for a simple shape of magnetic circuit analysis. Recently, because of the development of analytical techniques, the magnetic saturation of the core has designed to be high during even SPMSM design. The use of NdFeB permanent magnet (PM) can maximize flux density. By increasing the flux density, the torque density can be improved. However, when the magnetic saturation is high, there is a limitation to predict the performance by the magnetic circuit analysis in the 2-D plane due to the leakage flux in the axial direction. Therefore, 3-D FEA should be used for motor analysis where magnetic saturation is severe.

Many studies have been conducted to overcome the limitation of 3-D FEA and to analyze the electromagnetic characteristics of SPMSM, but only a few studies have addressed the axial leakage flux and its effect on motor characteristics [1]–[4]. Potgieter and Kamper [3] mainly addressed the effects of end-winding inductance and axial fringing by PMs on performance. However, there are limitations to the study due to some assumptions. In [4], the flux switching PM machine was analyzed by applying the lumped parameter magnetic circuit method. However, this paper is limited to the lumped parameter method [4]. In addition, many researchers have published papers on calculating the end-winding inductance of a stator winding [5]–[7]. However, the increase in inductance due to the end winding affects the terminal voltage or power factor in the analysis of the motor characteristics, but it is not related to the motor torque value according to the current input. This paper distinguishes not only the inductance change due to the axial leakage flux but also the torque degradation in the characteristic analysis.

In this paper, modeling method for 2-D FEA that can consider the axial leakage flux and its results is discussed. In order to reflect the axial leakage flux to the 2-D plane, the path of the axial leakage flux is grasped and can be projected onto the main leakage path of the 2-D model through a mathematical approach. Then, the proposed method is used to calculate the d- and q-axes inductance and linkage flux. After then, the d- and q-axes equivalent circuit analysis (ECA) was performed, and the analysis results of characteristics according to the FEA method were compared. It is the same as the previous study [8] in terms of the basic analysis method. However, in this paper, the application of the same theory deals with the analysis of parameter changes and motor characteristics according to load and speed. The accuracy of the proposed method is verified by comparing the 3-D analysis results with the experimental results of torque value according to current input values.

II. 2-D FEA Considering Axial Leakage Flux

A. Study Model of SPMSM

The analysis model of this paper is SPMSM with 10 pole and 12 slot as a motor for passenger car chassis parts drives. A motor has a stator diameter of 75 mm and an axial length of 13 mm which is a relatively small axial length compared to stator outer diameter. Due to the short axial length, the leakage magnetic flux at the axial end area has a great influence on the motor performance such as d- and q-axes inductance, power factor, and torque according to current. In order to improve the analysis accuracy instead of 3-D FEA, we present a novel approach to take account of axial leakage flux using 2-D FEA. In order to use this method, we used a model divided into six regions in the radial direction as shown in Fig. 1.

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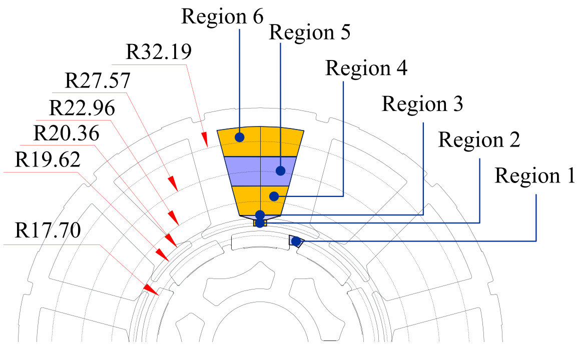

Fig. 1. Study model is divided into six regions.

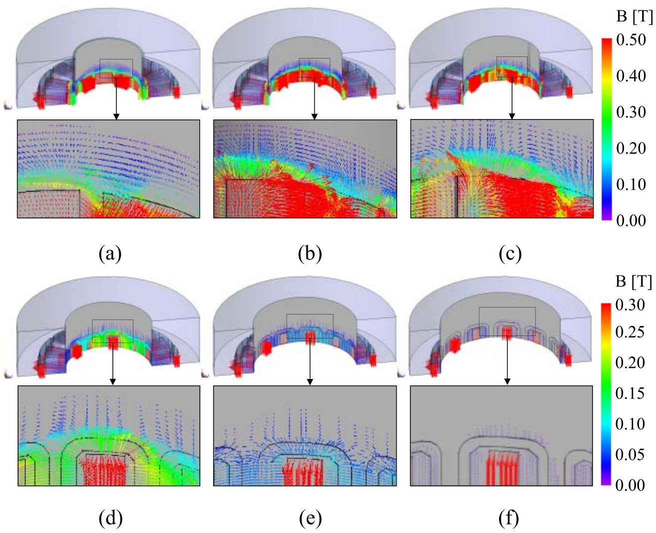

Fig. 2. Flux distribution of load condition for center radius of each area. (a) R17.7 mm. (b) R19.62 mm. (c) R20.36 mm. (d) R22.96 mm. (e) R27.57 mm. (f) R32.19 mm.

B. 3-D Flux Distribution of the Study Model

3-D FEA was performed to confirm the axial flux density distribution of the analysis model at load condition, as shown in Fig. 2. In order to easily display the magnetic flux density distribution of the 3-D model, a radial contour surface was applied based on the regions shown in Fig. 1. It is expressed in six regions [Fig. 2(a)–(f)]. Fig. 2(a) shows the PM area, and the flux density distribution is observed at the center of the radial direction of the PM. Fig. 2(b)–(f) shows stator areas. The radial distance from the air gap increases as the radial value increases. The axial leakage flux density of Fig. 2(a)–(c) is higher than 0.35 T at most. From Fig. 2(c) and (d), it can be seen that the flux density value is slightly decreased, but the value is larger than the no-load condition with the same region each. Although the results of the analysis are not shown, there is almost no axial leakage magnetic flux under the no-load condition. The axial leakage flux that appears during the load condition has a great influence on motor performance and parameters such as torque as well as d- and q-axes inductance and linkage flux. Therefore, axial leakage flux must be considered in the characteristics analysis.

C. 2-D FEA Considering Axial Leakage Flux

If it is possible to reflect the axial leakage flux into the 2-D FEA, the time and effort for performing the 3-D FEA will be considerably saved. In order to consider the magnetic flux leaking into a 3-D path on a 2-D plane, we decided to introduce a permeance factor μ_{rf} in the main leakage path such as slot area and area between PMs which is shown in Fig. 1. After applying the μ_{rf} into each region of the model, the proposed 2-D FEA method is performed in the same manner as the conventional 2-D FEA. Fig. 3 shows the permeance of main leakage and the axial leakage path. Assume a leakage magnetic field as a semicircle is based on the flux density distribution as a result of 3-D FEA. The permeance of the main leakage that path on the 2-D plane is defined as P_{mn}. The P_{sen} and P_{ten} are defined as the permeance to the leakage from the tooth to the tooth or between the pole and the pole in the axial direction of the air region. P_{mn}, P_{sen}, and P_{ten} are shown in (1) to (3), respectively. The value 0.264 in (2) is a constant that does not change when calculating the semicircular shape of permeance [4]. Considering both ends of the motor, the total permeance $P_{\text{n\_total}}$ is calculated as shown in (4), and then μ_{rf} is introduced to express (5). Finally, μ_{rf} is arranged in the form of dividing the permeance of the main leakage to the total permeance as shown in (6). The parameters used in the equations are the same as those in the previous study [8]. In the formula, the subscript n denotes the nth region, and R_{ao-n} and R_{ai-n} in (3) mean the outer and inner diameters of the nth air region, respectively. L_{stk} is the stack length

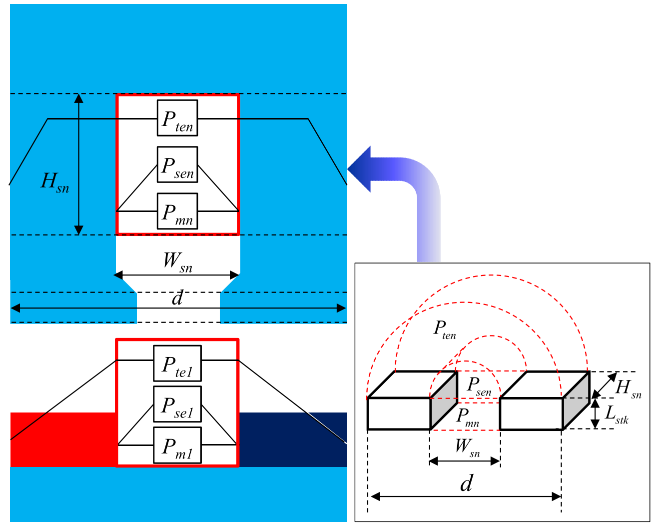

Fig. 3. Modeling of permeance on each leakage path.

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

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

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

$$P_{n\_\text{Total}} = 2\,(P_{\text{sen}} + P_{\text{ten}}) + P_{mn} \tag{4}$$

$$P_{n\_\text{Total}} = \mu_{\text{rf}} \cdot P_{mn} \tag{5}$$

$$\mu_{\text{rf}} = \frac{P_{n\_\text{Total}}}{P_{n_m n}}. \tag{6}$$

In order to verify the accuracy of the proposed 2-D FEA, flux density distributions were compared according to the analysis method. Fig. 4(a) shows the result of 3-D FEA, and

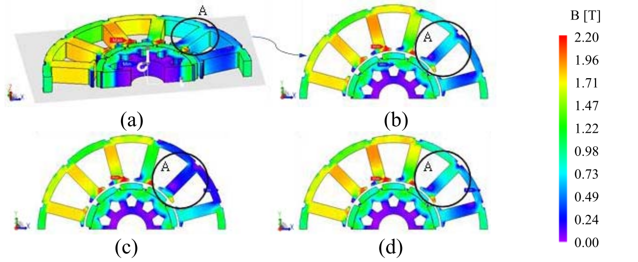

Fig. 4. Flux distribution according to FEM method. (a) 3-D FEA. (b) 3-D FEA on contour plane. (c) Conventional 2-D FEA. (d) Proposed 2-D FEA.

Fig. 4(b) shows the magnetic flux density distribution which is displayed with the contour surface at the center of the 3-D model. It can be seen that the flux density distribution obtained from 3-D FEA is more similar to the result of the proposed method than the conventional 2-D FEA results, particularly notation "A" area.

III. Characteristics Analysis

In this paper, the parameters are calculated by using the proposed 2-D FEA and the results of the characteristics analysis are presented by performing the d- and q-axes ECA.

A. Parameter Calculation for Characteristics Analysis

The d- and q-axes inductance and the no-load linkage flux according to current and current angles were calculated to perform the d- and q-axes ECA. The current was applied to nine steps from 5 to 65 A_{rms}. The current phase angle was also calculated as nine steps from 0° to 90°. The d- and q-axes inductances and no-load flux linkages were calculated using (7) to (9), respectively. In (7), i_d is the d-axis current, and Φ_d is the d-axis flux. The Φ_o in (8) is the total linkage flux at load condition, and α is the phase angle between total linkage flux and the no-load linkage flux. The Φ_{oa} in (9) refers to the no-load linkage flux considering the saturation of magnetic circuit. More details are covered in other studies [9]

$$L_d = \frac{\Delta \boldsymbol{\Phi}_d}{\Delta i_d} \tag{7}$$

$$L_q = \frac{\boldsymbol{\Phi}_o \cdot \cos\alpha}{i_q} \tag{8}$$

$$\boldsymbol{\Phi}_{oa} = \boldsymbol{\Phi}_o \cdot \cos\alpha + L_d \cdot i_d. \tag{9}$$

Fig. 5 shows the d- and q-axes inductance and Φ_{oa} calculated from the conventional 2-D FEA and the proposed method. The d- and q-axes inductances of the proposed method are generally larger than those obtained by the conventional analysis method. When the proposed method is used for inductance calculation, the axial leakage magnetic flux is reflected in the slot leakage flux, so that the value is generally increased due to the increase in the leakage inductance. On the other hand, in the case of Φ_{oa}, there is no difference in the results obtained by the two analysis methods when the current size is small. However, as the current magnitude increases, the value decreases significantly when the proposed method is used. The proposed method can accurately reflect the phenomenon that the linkage flux becomes smaller due to the axial leakage flux that increases as the current amplitude.

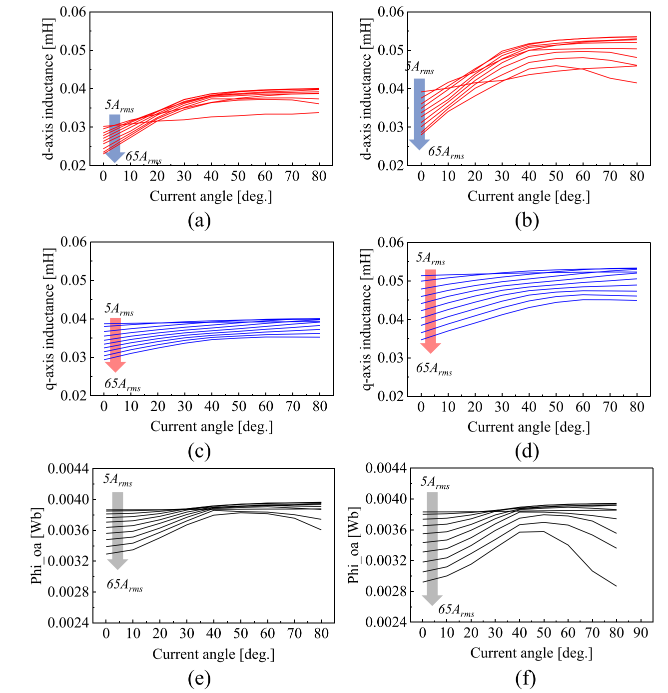

Fig. 5. Parameters for performing the d- and q-axes ECA. (a) L_d_conventional FEA. (b) L_d_proposed FEA. (c) L_q_conventional FEA. (d) L_q_proposed FEA. (e) Φ_{oa}_conventional FEA. (f) Φ_{oa}_proposed FEA.

B. d- and q-Axes Equivalent Circuit Analysis

The d- and q-axes ECA is useful for the characteristics analysis of the permanent magnet synchronous motor [10]. We compared the characteristics according to FEA method through the d- and q-axes ECA using the parameters of the study model calculated above. The results of the d- and q-axes ECA according to the FEA method are shown in Fig. 6. When the proposed 2-D FEA is used, the maximum torque is reduced by about 11.6% under the same current compared to conventional 2-D FEA as shown in Fig. 6(a) and (b). On the other hand, the 3-D FEA results are in good agreement with the torque obtained by the proposed method. Therefore, the output power of the proposed method is similar to that of 3-D FEA as shown in Fig. 6(c). Fig. 5 presents that d- and q-axes inductances calculated by the proposed 2-D FEA are larger than those of the conventional method. Therefore, as shown in Fig. 6(c), the power factor is also analyzed to be small. In addition, the power factor calculated by 3-D FEA is also close to the power factor obtained by the proposed method than the conventional method. Fig. 6(e) and (f) shows the d- and q-axes inductances and Φ_{oa} of the study model on the torque–speed characteristics. When the proposed 2-D FEA is applied to characteristics analysis, it can be confirmed that the d- and q-axes inductance is increased and the Φ_{oa} is decreased. Especially, by using the proposed 2-D FEA, which considers the axial leakage flux, it can be confirmed that the reduction of Φ_{oa} directly affects the torque calculation.

IV. Experimental Verification

In order to verify the characteristics analysis by using the proposed method, a current versus torque experiment was performed. Overall performance cannot be measured due

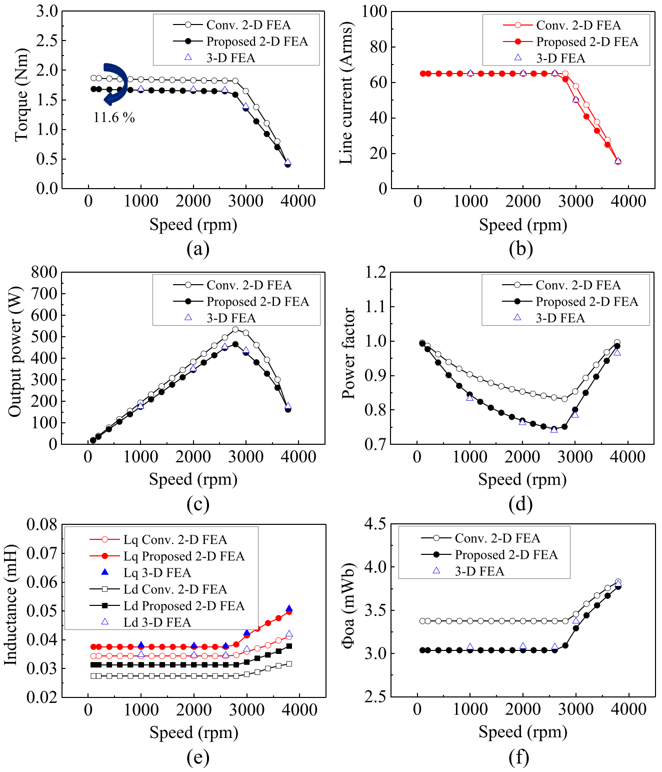

Fig. 6. Comparison of characteristics according to FEA method. (a) Torque–speed. (b) Line current–speed. (c) Output power–speed. (d) Power factor–speed. (e) Inductance–speed. (f) Φ_{oa}–speed.

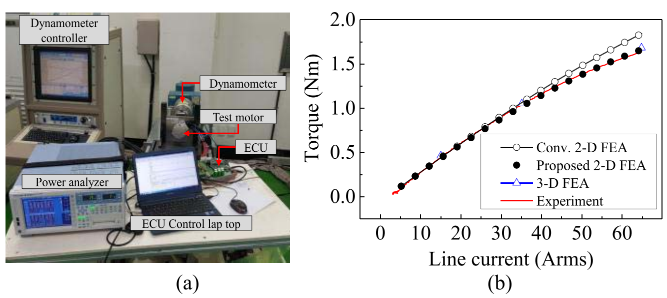

Fig. 7. Experimental verification. (a) Test setup. (b) Comparison of current versus torque.

to the characteristics of the 12 V_{DC} drive system, which is sensitive to the effects of external systems such as controllers and cables. Fig. 7(a) shows the test setup, and Fig. 7(b) shows the torque value according to the FEA method by changing the current value. Under the small current condition, the experimental and all analysis results have similar values. Since the flux saturation is small, it is judged that the axial leakage flux has little effect on the torque. On the other hand, as the current increases, the conventional 2-D FEA results in an error with the experimental value. However, the proposed 2-D FEA and 3-D FEA results are good agreement with experimental results.

V. Conclusion

It is important to consider the axial leakage flux in analysis of motors with high saturation. The high magnetic flux density generates leakage flux in the axial direction as well as in the 2-D plane. In this case, 3-D FEA is required for accurate prediction of motor performance, but it is difficult to use it for design because of time, efforts, and cost issues. In this paper, we propose a method to consider the leakage magnetic flux in the axial direction in 2-D FEA and analyze the characteristics of the analysis. The influence of the axial leakage magnetic flux on the parameters and characteristics of the motor are studied through the comparison of the FEA method. It was confirmed through experiments that the axial leakage flux directly affects not only the voltage, power factor but also the torque and output power of the motor. Using this analysis method instead of 3-D FEA, it can be usefully applied to the design stage to analyze various models and in parameter calculation according to current and current angles.

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