

Design of Equivalent 2-D Finite Element Analysis Model for AFPMM Considering the End Effects in Radial Direction

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With recent advancements in analysis and manufacturing technologies, interest in axial flux permanent magnet motors (AFPMMs) has been increasing. Accurate analysis of AFPMMs requires 3-dimensional finite element analysis (3-D FEA). While 3-D FEA offers high accuracy, it demands significant computational time and resources. To address these limitations, this paper proposes an equivalent 2-dimensional finite element analysis (2-D FEA) model. The proposed model improves the accuracy of 2-D analysis by considering the radial end effect. By dividing the 3-D model radially to construct the 2-D equivalent model, the analysis accuracy is enhanced by considering the leakage flux in the innermost and outermost radial regions. The precision of the equivalent 2-D FEA model will be validated through comparisons with 3-D FEA results and experimental data.

Index Terms— Electric Vehicles, Finite Element Analysis, Permanent Magnet Motors, Permeability

I. INTRODUCTION

With the growing global focus on electrification of powertrain systems, the demand for high-efficiency, high-performance electric motors is rising. Axial flux permanent magnet motors (AFPMMs) have recently gained recognition for their unique design and are particularly valued as efficient solutions for hybrid electric vehicle drive motors, especially in applications with limited installation space. However, the 3-dimensional magnetic circuit and complex structure of AFPMMs result in significant time and resource requirements for electromagnetic analysis, posing challenges for practical applications [1].

To accurately analyze AFPMMs, 3-D FEA must be performed. However, 3-D FEA requires significantly more time and computational resources compared to 2-D FEA, leading to active research on overcoming these limitations [2]. This study proposes an equivalent 2-D FEA model to address the challenges associated with 3-D FEA in AFPMMs, reducing analysis time while maintaining accuracy. First, a 3-D FEA model is constructed for the target motor, and the magnetic flux density distribution is analyzed to identify the leakage flux path at the radial end of the AFPMM. To simplify the construction of the equivalent 2-D FEA model, the 3-D FEA model is divided into n segments (n is equal to natural number except zero) in the radial direction, forming a fan-shaped structure. During this process, the divided 3-D FEA model and the original non-divided model are ensured to have identical volumes for each component (rotor, permanent magnet, stator, and coil). Each of the n divided sectors is then converted into an equivalent 2-D FEA model.

The converted equivalent 2-D FEA model adopts the form of a linear machine, as introduced in previous research [3]. Before analyzing the 10 linear machine models, additional steps are required to account for radial leakage flux in the equivalent 2-D FEA models corresponding to the innermost and outermost segments of the 3-D FEA model. Using the magnetic projection method, an equivalent 2-D FEA model is constructed to include the radial leakage magnetic flux component [4]. The accuracy

of the proposed equivalent 2-D FEA model for AFPMM will be validated by comparing its analysis results with those of the 3-D FEA model and experimental data.

II. ANALYSIS OF AFPMM CONSIDERING RADIAL END EFFECTS

A. Definition of Analysis Model

Fig. 1 shows normal and 10-segmented 3-D FEA models used in the analysis. Fig. 1(a) shows a traditional 3-D FEA model where the entire motor is not divided into a fan-shaped structure from the origin, and a model where the motor is divided into 10 fan-shaped segments based on the origin. The analysis results of the two models are the same. Fig. 1(b) and 1(c) show the geometries where the permanent magnet, stator, and coil are divided into 10 segments. The volume of each component in the 3-D FEA model is preserved in the equivalent 2-D FEA model. For the equivalent 2-D FEA model, the area of each component is multiplied by the radial length divided into n segments, and calculated volume is compared with the 3-D FEA model. Modeling is performed on an equivalent 2-D FEA in the form of a linear geometry based on the central radius of each segment.

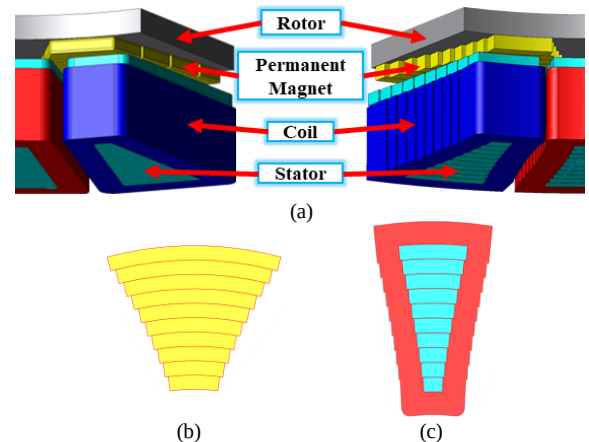


Fig. 1. Analyzed model. (a) Shape of initial 3-D FEA model and 3-D FEA model divided into 10 segments. (b) Shape of segmentized permanent magnet. (c) Shape of segmentized stator and coil.

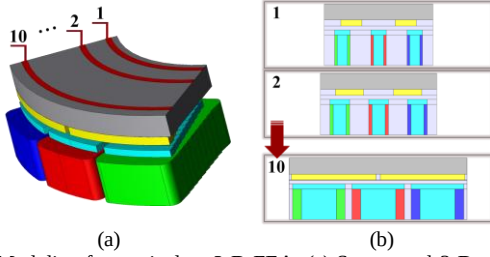


Fig. 2. Modeling for equivalent 2-D FEA. (a) Segmented 3-D model. (b) Equivalent 2-D model.

B. 2-D Equivalent Considering Radial End Effects

To accurately convert a 3-D FEA model into a 2-D FEA model, the 3-D model must be divided into multiple segments while ensuring that the volumes of the rotor, permanent magnet, and stator remain consistent. Fig. 2 illustrates the process of deriving 10 equivalent 2-D FEA models from the segmented 3-D FEA model. This procedure also applies equally to 3-D FEA models divided into any number of segments. During the material information input process, first and n th layer differ from other layers because the radial leakage flux component is not considered in the equivalent 2-D FEA model. This is because the leakage flux occurs in the radial direction in the first and n th layers. Therefore, these differences must be addressed to achieve analysis accuracy comparable to that of the 3-D FEA model.

A conceptual diagram for calculating the transmittance of a radially flowing magnetic flux path in the radial and axial directions due to the leakage and fringe effect is shown in Fig. 3. Equations (1) through (5) describe the key parameters of the transmittance in the 2-D FEA model. Equation (1) defines the transmittance of the main path. Equation (2) provides the transmittance formula, modeled as a semicircle centered on the air region. Equation (3) characterizes the permeability of the semi-ring structure adjacent to the air region. Equation (4) expresses the total transmittance as the sum of the main path and two radial path contributions. Finally, Equation (5) specifies the transmittance coefficient for the air region, calculated as the ratio of the main transmittance to the total transmittance. By assigning the calculated permeability coefficient (a value greater than 1) to the air region, we project the magnetic flux flowing through the radial magnetic path onto the main magnetic path. Transmittance coefficient application is applied only to the first and n th layers to take into account radial leakage flux and fringe effects. The experimental results and the 3-D FEA of the line to line back EMF results exhibit a high degree of similarity. The proposed method reduces the error rate compared to the conventional 2-D equivalent model. In the full paper, we will propose the optimal number of segments and methods to further minimize the error rate.

$$P_{sm,n} = \mu_0 \cdot \frac{l_{tooth,n} \cdot h_{tooth,n}}{w_{slot,n}} \quad (1)$$

$$P_{sse,n} = 0.264 \cdot \mu_0 \cdot h_{tooth,n} \quad (2)$$

$$P_{ste,n} = \mu_0 \cdot (h_{tooth,n} / \pi) \cdot \ln(1 + \frac{w_{tooth,n}}{w_{slot,n}}) \quad (3)$$

$$P_{st,n} = P_{sm,n} + P_{sse,n} + P_{ste,n} \quad (4)$$

$$\mu_{rf,n} = P_{sm,n} / P_{st,n} \quad (5)$$

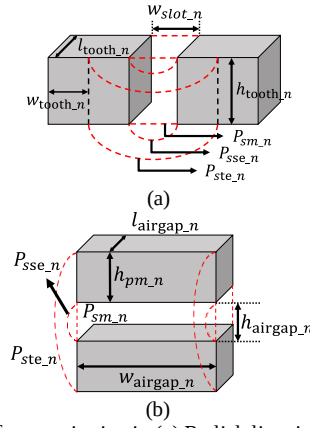


Fig. 3. Leakage path of magnetic circuit. (a) Radial direction. (b) Axial direction.

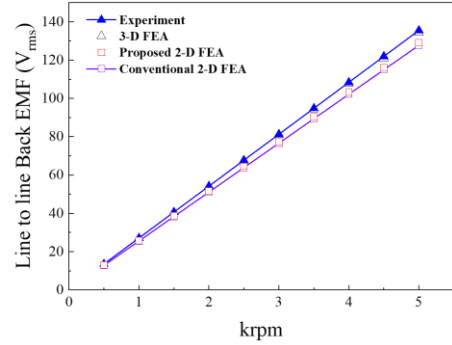


Fig. 4. Comparison of experimental data, 3-D FEA, proposed 2-D FEA and conventional 2-D FEA line to line back EMF.

III. CONCLUSION

This study proposes a equivalent 2-D FEA model for AFPMMs that accounts for radial leakage flux and fringe effects. The proposed method significantly reduces the computational time while maintaining the accuracy similar to 3-D FEA. In the full paper, we will minimize the error and compare the characteristics and analysis time of the proposed 2-D FEA and 3-D FEA.

ACKNOWLEDGEMENT

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