

Radial Flux Leakage-Integrated Quasi-3D Approach for Accurate Axial Flux PM Motor Analysis

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Axial flux permanent magnet (AFPM) motors have drawn significant attention due to their compact size, high torque density, and broad applicability. However, accurately designing an AFPM motor often requires computationally intensive three-dimensional finite element analysis (3D FEA). To alleviate this, a quasi-three-dimensional (quasi-3D) model can be employed, in which the AFPM motor's geometry is represented in a flattened, two-dimensional equivalent form. The quasi-3D model offers an efficient alternative but typically fails to consider important factors such as radial flux leakage. This limitation can lead to predicted voltage and torque discrepancies compared to 3D FEA results. In this article, we improve the conventional quasi-3D model by calculating the radial leakage path's permeance and incorporating it into the two-dimensional analysis. As a result, the improved quasi-3D model shows a better correlation with 3D FEA. The improved quasi-3D model significantly reduces computational cost with minimal sacrifice of precision compared to 3D FEA, enabling faster and more reliable design processes.

Index Terms— Axial flux permanent magnet (AFPM), Permeance, Quasi-3D model, Radial flux leakage path, Three-dimensional finite element analysis (3D FEA)

I. INTRODUCTION

THE design of axial flux permanent magnet (AFPM) motors relies on three-dimensional finite element analysis (3D FEA), which can be computationally intensive and time-consuming. To address these challenges, simplified methods such as the quasi-three-dimensional (quasi-3D) model have been introduced, representing the AFPM geometry in a flattened, two-dimensional equivalent form [1]. However, the conventional quasi-3D model does not fully capture critical effects, including radial flux leakage and end coil inductance [2], leading to discrepancies in analysis results. Various strategies have been investigated to mitigate these discrepancies, such as employing magnetic equivalent circuits [3]. Meanwhile, [4] demonstrates how omitted flux leakage paths in two-dimensional analysis can be integrated by mathematically adjusting the permeance and improves the overall accuracy without additional computation burden.

In this paper, we propose an improved quasi-3D model that integrates the radial flux leakage path by incorporating the permeance of the radial leakage path into the two-dimensional analysis. As a result, the improved quasi-3D model achieves better correlation with 3D FEA while maintaining computational efficiency.

II. IMPROVED QUASI-3D ANALYSIS

A. Motor Specifications

The target motor is a single-stator, single-rotor AFPM. Table I summarizes the key specifications, including material properties and representative operation points. The two operation points and no-load condition are used to evaluate the accuracy of the improved quasi-3D model in different saturation conditions, guaranteeing a broader validation.

TABLE I
MOTOR SPECIFICATION AND OPERATION POINTS

Specification	Value
Pole / Slot	48 / 36
Magnet residual flux density	0.424 T
Stator / Rotor material	50H600 / 50H1300
Operation point 1	100 rpm, 5.4 Nm
Operation point 2	1500 rpm, 3.4 Nm

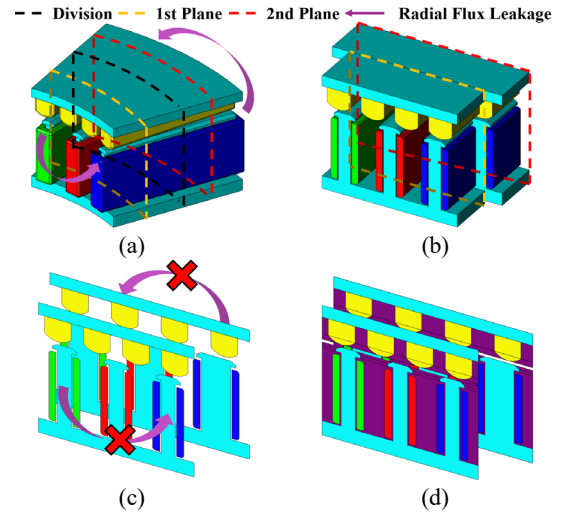


Fig. 1. AFPM analysis methods. (a) 3D Model. (b) Equivalent linear model. (c) Conventional quasi-3D model. (d) Improved quasi-3D model.

B. Conventional Quasi-3D Analysis

Fig. 1 shows various methods for the analysis of an AFPM. Fig. 1(a) shows the reference 3D model. The geometry is first transformed into a linear model to reduce analysis effort, as shown in Fig. 1(b), enabling the 2D-compatible conventional quasi-3D model depicted in Fig. 1(c). This paper divides the model into two planes to retain accuracy. However, this conventional quasi-3D model no longer accounts for radial flux leakage that naturally occurs in the original 3D model.

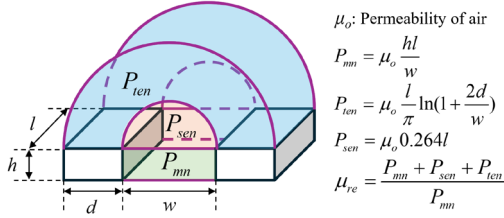


Fig. 2. Permeance calculation for radial leakage flux [5].

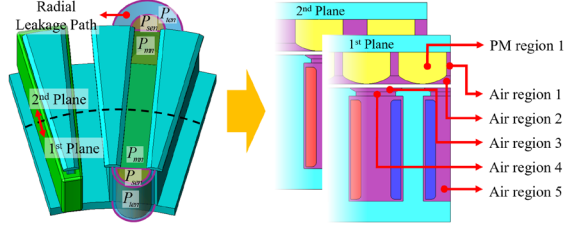


Fig. 3. Concept of radial leakage path, plane division, and separated region.

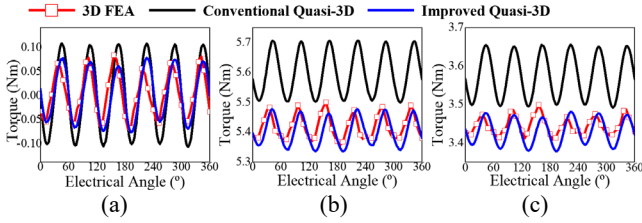


Fig. 4. Torque waveform comparison between 3D FEA, conventional, and improved quasi-3D. (a) No-load. (b) Operation point 1. (c) Operation point 2.

TABLE II
EFFECTIVE RELATIVE PERMEABILITY OF EACH REGION

Region	1 st Plane μ_{re}	2 nd Plane μ_{re}
PM region 1	1.264	1.334
Air region 1	1.070	1.152
Air region 2	1.145	1.190
Air region 3	1.197	1.239
Air region 4	1.191	1.224
Air region 5	1.196	1.249

C. Improved Quasi-3D Analysis

To overcome the inability of the conventional quasi-3D model to include radial leakage flux, we propose an improved quasi-3D model, as depicted in Fig. 1(d). Each of the two planes now incorporates a dedicated radial flux leakage path—one for the inner side and another for the outer side—by calculating an effective relative permeability μ_{re} using the expressions in Fig. 2. To ensure accuracy, μ_{re} is calculated for six different regions based on their geometry and material characteristics, as shown in Fig. 3. The resulting μ_{re} values are provided in Table II. This way, the radial flux path is projected into the two-dimensional analysis, allowing the model to capture radial leakage effects without additional computation.

D. Error Comparison of Quasi-3D Models Against 3D FEA

Fig. 4 presents the comparative waveforms of torque for multiple operating points under the conventional and improved quasi-3D models alongside the reference 3D FEA. Table III summarizes that the improved quasi-3D model exhibits lower errors than the conventional quasi-3D model, particularly for the cogging torque and torque ripple. The errors for the no loadback electromotive force (BEMF) and average torque decrease the discrepancy to less than 1% in all operation points,

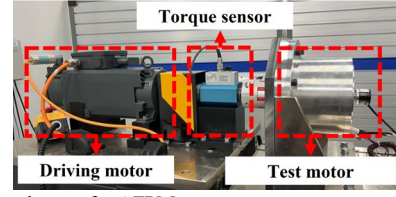


Fig. 5. Experimental setup for AFPM

TABLE III
ERROR COMPARISON OF EACH METHOD AGAINST 3D FEA

Operation point	Analysis result	Conventional quasi-3D (%)	Improved quasi-3D (%)
No-load	Cogging torque	39.62	0.92
	BEMF	3.20	0.43
	Average torque	3.33	0.27
1	Torque ripple	39.35	1.87
	Induced voltage	1.74	4.08
	Average torque	3.76	0.43
2	Torque ripple	75.76	14.82
	Induced voltage	30.59	9.23

confirming its enhanced accuracy. As for the induced voltage, error increased by 2.3%p at operation point 1. Still, at operation point 2, where the induced voltage is critical due to high-speed operation, the error decreased by 20%p. Hence, these results highlight that considering the radial flux leakage path into the quasi-3D model enhances agreement with 3D FEA without additional computation burden. Fig. 5 shows the experimental setup to verify the proposed method and motor. The target motor is in the course of manufacture, and the test result will be included in the full paper.

III. CONCLUSION

This paper presented an improved quasi-3D model for AFPM motors that considers the radial flux leakage path in the two-dimensional analysis. By incorporating the radial leakage permeance, the improved quasi-3D model demonstrates better agreement with 3D FEA results regarding BEMF, induced voltage and cogging torque, average torque, and torque ripple at the examined operating points. This improvement comes without increasing computational cost, making the proposed method a promising tool for more efficient and accurate AFPM motor design and optimization. Future work will include fabrication and experimental verification of the AFPM using the proposed method.

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