

A Novel Method for Optimal Design of AFPMMs Combining Static 3D FEA and Quasi-3D FEA to Alleviate Computational Burden

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In this study, an optimal design method for axial flux permanent magnet motors (AFPMMs) is proposed by integrating a combined analysis approach that utilizes static three-dimensional (3D) finite element analysis (FEA) and quasi-3D FEA, with a kriging-based optimization algorithm. This approach aims to alleviate the computational burden typically encountered in the design optimization of AFPMMs. The proposed method addresses challenges related to complex magnetic interactions and high computational costs by alleviating FEA time through iterative improvements in 3D model analysis. Simultaneously, the kriging surrogate model efficiently approximates the design space, ensuring precision while significantly reducing computation time. The proposed optimization strategy enhances significant performance indicators such as torque density and torque ripple, demonstrating its effectiveness in optimal design of AFPMMs. Moreover, the methodology is broadly applicable to other complex electromagnetic systems, particularly radial flux permanent magnet motors (RFPMMs) with overhang structures that require 3D FEA. This approach offers motor designers and engineers an efficient optimization framework, enabling rapid and accurate derivation of optimal design solutions while minimizing computational time.

Index Terms—Analysis method, axial flux permanent magnet motor, finite element analysis, kriging, optimal design, quasi-3D, surrogate model, synchronous motor.

I. INTRODUCTION

AXIAL flux permanent motors (AFPMMs) have received significant attention in the fields of electric vehicles and propulsion systems due to their high torque density compared to conventional radial flux machines. Also, the compact design of AFPMMs enables operation at a reduced current density, which leads to lower power losses compared to traditional induction machines [1]. The AFPMM topology of YASA type is shown in Fig. 1 (a).

However, they also present significant challenges, with torque ripple being the most critical issue. Various approaches have been developed to mitigate torque ripple, as it poses significant issues in electric motors and driving stability. Therefore, designing effective strategies to reduce torque ripple is essential for enhancing overall motor performance.

In the design process for AFPMMs, accurate and efficient performance evaluation methods are essential. From an optimization perspective, however, the ability to accurately and quickly analyze motor performance is equally critical [2]. While three-dimensional (3D) finite element analysis (FEA) is highly effective for analyzing the complex magnetic circuits of AFPMMs, its computational intensity and time requirements make it unsuitable for efficient optimization. Even with simplified models, such as the 1/6 periodic model shown in Fig. 1(b), the computational burden remains significant due to the intricate nature of 3D magnetic field analysis.

To address these limitations, quasi-3D FEA method has been proposed as a faster alternative by simplifying the AFPMMs [3]–[4]. In particular, two-dimensional (2D) FEA derived from linear motor models is crucial for optimizing AFPMM designs efficiently. However, this approach introduces analysis errors, as it cannot account for flux variations along the radial direction including edging effect. Finally, its limitations can result in

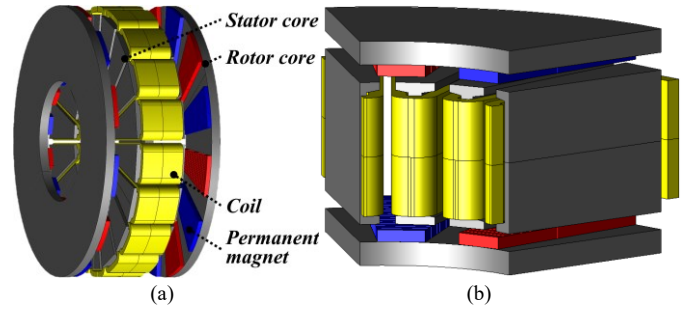


Fig. 1. 3D model of YASA type AFPMM. (a) 12 pole 18 slot motor. (b) 1/6 periodic model.

TABLE I
SPECIFICATION OF INITIAL MODEL

Parameter	Value
Pole / Slot	12 / 18
Stator inner / outer diameter [mm]	80 / 180
Rotor inner / outer diameter [mm]	80 / 180
Stacking length (Stator/Rotor) [mm]	50 / 50
Air gap [mm]	1.5
Core material	35JN230
Permanent magnet material	N42SH-R
Operating temperature [°C]	50

significant errors, emphasizing the necessity for improved methodologies.

Therefore, this paper proposes a point-specific analysis method (PSAM) that significantly alleviates analysis time while maintaining high accuracy. Since PSAM evaluates the motor performance of 3D model using FEA, it accurately calculates the electromagnetic characteristics. Furthermore, it minimizes time consumption by analyzing only two specific points rather than conducting a full periodic analysis over one electrical angle cycle. Consequently, the proposed method enables the efficient and rapid design of optimal AFPMMs, eliminating the excessive computational burden of traditional approaches.

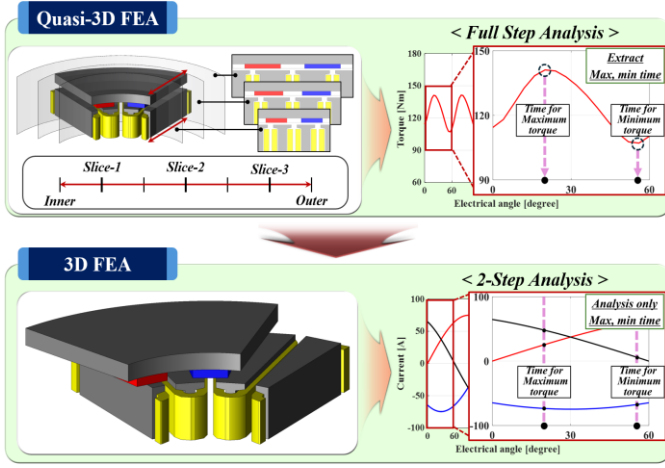


Fig. 2. Conceptual schematic of PSAM.

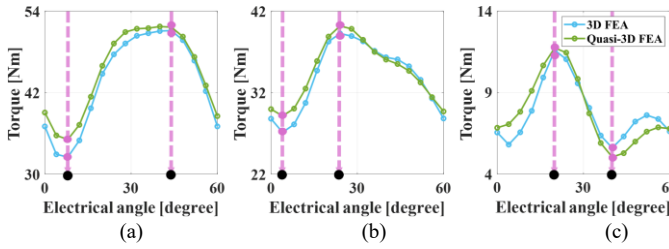


Fig. 3. Compared maximum and minimum torque positions between 3D FEA and Quasi-3D FEA.

II. PROPOSED POINT-SPECIFIC ANALYSIS METHOD

Fig.2 illustrates the conceptual schematic of PSAM. The proposed analysis method is based on quasi-3D FEA, which uses a one-period electrical angle analysis to identify two points corresponding to the maximum and minimum torque. Static 3D FEA is then performed exclusively at these extracted time points. To calculate the average torque and the fundamental voltage component, the initial step FEA (ISF) is applied to evaluate the initial position of rotor, thereby reducing computation time [5]. By combining the ISF method with the PSAM approach, it becomes possible to effectively track torque ripple values.

Fig.3 (a), (b), and (c) present the torque results for models with initial model specification as listed in Table.1. These results were obtained under a current density of $10 \text{ [A}_{\text{rms}}/\text{mm}^2]$ and current phase angles of $0, 40, \text{ and } 80^\circ$, respectively. The maximum and minimum torque positions identified through quasi-3D FEA closely align with those obtained from 3D FEA, confirming the reliability and accuracy of the proposed method. Performing static 3D FEA at these specific points yields more accurate minimum and maximum torque values compared to using quasi-3D FEA only. Therefore, the proposed PSAM method can be effectively applied to the optimal design of AFPMMs by providing rapid and accurate torque ripple values, designed to supplement the limitations of quasi-3D FEA and enhance the accuracy of performance predictions.

III. OPTIMIZATION ALGORITHM

FEA is crucial for analyzing the electrical and magnetic characteristics of devices like AFPMMs and RFPMMs. The

complexity of solving nonlinear equations, particularly due to magnetic saturation effects, makes FEA time-consuming. This challenge becomes more significant in multimodal optimization problems, such as the optimal design of electric motors, where the computational time required for FEA can severely affect the efficiency of the design process. Accordingly, the optimal design is performed using a optimization algorithm-based kriging surrogate model.

A. kriging interpolation

Kriging is a technique used to analyze and utilize the characteristics of spatially distributed data to estimate the value of the desired location. In other words, it is one of the methods mainly used in optimal design to derive an optimal solution by creating a surrogate model by interpolating the results obtained from FEA.

B. Objective function

For optimal design of AFPMMs, torque density and torque ripple are selected as the significant performance indicators. The objective function for the optimization algorithm is formulated using a weighted sum approach. To simultaneously maximize torque density and minimize torque ripple, the weights are set to an equal ratio of 1:1.

IV. CONCLUSION

By utilizing the similarity in the time points corresponding to maximum and minimum torque between Quasi-3D and 3D FEA results, this study proposes PSAM, an analysis method that significantly alleviates computation time while maintaining high accuracy. The proposed method is integrated with a optimization algorithm-based kriging surrogate model to derive an optimal design solution. The detailed optimization process and results are discussed in the full paper.

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