

FEM Modeling of Rare Earth Magnets with Grain Boundary Diffusion Used in Large Size Permanent Magnet Electrical Machines

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During the optimal design of a large-size permanent magnet (PM) electrical machine, its electromagnetic performance and the PM anti-demagnetization capability should be iteratively analyzed with finite element method (FEM). If the PM has been processed with grain boundary diffusion (GBD), its magnetic property varies inside it. This will lead to high modeling complexity and computation burden. Therefore, it is proposed to model the PMs as a homogeneous equivalent material in FEM when calculating the machine overall performance. Whilst in the anti-demagnetization analysis, the FEM field results in the homogeneous PM are extracted and applied in the analytical nonuniform model that reflects the actual GBD PM to estimate its demagnetization situation. The proposed method avoids excessive detailed modeling of the PM within the large machine model in FEM, therefore improving the computation efficiency.

Index Terms—Permanent magnet, grain boundary diffusion, homogeneous equivalent model, nonuniform model, large-size electrical machine, multi-dimensional finite element analysis.

I. INTRODUCTION

LIGHT rare earth permanent magnets (PMs) such as NdFeB added with Ce can be used in electrical machines so as to reduce the consumption of expensive materials of Nd and Pr, while the PMs need to be processed with grain boundary diffusion (GBD) to enrich the coercivity. The machine electromagnetic performance and the PM anti-demagnetization capability must be optimized during the design stage [1]. This is typically implemented with iterative finite element method (FEM) calculations, which demand significant computation resources. Moreover, the GBD makes the magnetic property vary inside the PM [2], thus it needs to be modeled as a finely-meshed nonuniform material to enhance the accuracy, further increasing the computation burden. Furthermore, when the machine has a large overall size at the scale of meters, the magnets are usually at the scale of centimeters, whilst the GBD thickness of PM is of millimeters only. Such a wide scale range makes FEM much more complex and time-consuming.

In this paper, a semi-analytical modeling method is proposed for the GBD PM within a large-size electrical machine. First, a homogeneous equivalent PM model, instead of the nonuniform one, is used for calculating the overall electromagnetic performance of the whole machine with FEM. In this case, the millimeter-level GBD is avoided, thus the multi-scale FEM in the large-size machine is simplified. Second, with the same model, the field distribution in the PM under demagnetization current can be extracted. An analytical nonuniform model is defined for the actual GBD PM to analyze its demagnetization situation with the pre-extracted field. This prevents extremely detailed modeling and refined meshing in FEM while maintains high accuracy. To simplify the nonuniform model, the GBD PM is divided into several layers, assuming the same property in each layer. The sizes

and magnetic property of each layer can be obtained by measuring the actual GBD PM.

II. ELECTROMAGNETIC PERFORMANCE ANALYSIS

A unit of a 72-slot 60-pole large-size PM machine, with the stator outer diameter as 1610 mm, is shown in Fig. 1. Its ratings include 400 kW, 60 r/min and 26.4 Arms per phase. The tangentially magnetized PMs have been treated with GBD of Tb, and their nonuniform magnetic property is represented with 5 layers. The PMs of each pole are of 40 mm×20 mm×50 mm with 14 axial segments, and the thickness of layer 1 to 4 is set as 1.25 mm. The demagnetization curves of the GBD PM at different layers are shown in Fig. 2. The 1st layer has the richest GBD with lowest remanence but strongest anti-demagnetization capability, whilst the 5th one has no more GBD effect and is the same as the original PM.

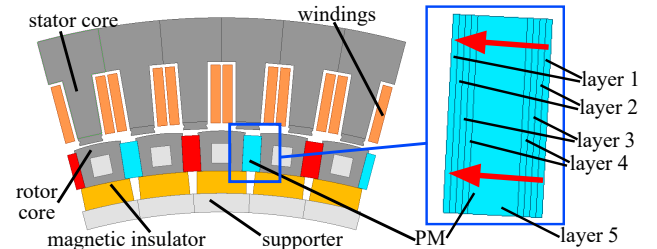


Fig. 1. A unit of studied large-size PM machine and the nonuniform PM model, with red arrows indicating magnetization direction.

The homogeneous equivalent PM model, which reflects the overall performance of the GBD PM, is proposed by performing a weighted average of the PM properties at different depth, assuming that the magnetic flux density is identical across various locations of the PM. Its demagnetization curve is also shown in Fig. 2. By employing the homogeneous PM

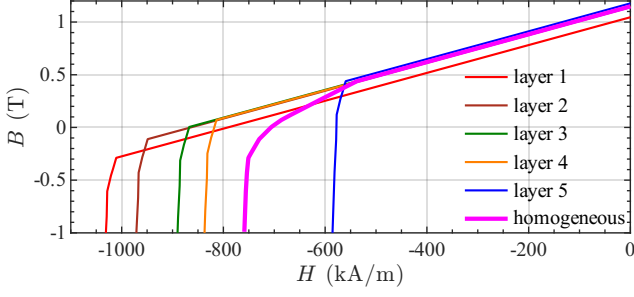


Fig. 2. Demagnetization curves of GBD PM at different layers at 120 °C.

model in the FE model of the unit machine instead of the nonuniform one, the modeling complexity and computation load can be reduced. The number of FEM meshing elements decreases from 8448 with the nonuniform PM model to 7600 with the homogeneous one, directly resulting in shorter calculation time (188s v.s. 169s). This advantage becomes rather significant when FEM iteration up to thousands of times is carried out for machine optimization. Moreover, the machine electromagnetic performance calculated with the two PM models reveals less than 1% difference. Therefore, the proposed homogeneous model exhibits both computation efficiency and accuracy in evaluating the machine electromagnetic performance.

III. ANTI-DEMAGNETIZATION ANALYSIS

In the anti-demagnetization analysis, the demagnetization depth can be characterized with demagnetization coefficient $\eta(x, y)$, which is defined as

$$\eta(x, y) = B'_r(x, y) / B_r(x, y) \quad (1)$$

where $B_r(x, y)$ and $B'_r(x, y)$ are the remanence before and after irreversible demagnetization at location (x, y) within the PM. However, $\eta(x, y)$ derived from the homogeneous model (denoted as $\eta_{\text{hom}}(x, y)$) cannot reflect the actual demagnetization distribution of the GBD PM due to neglect of the nonuniform anti-demagnetization capability. Nevertheless, considering the consistency of machine performance between the homogeneous equivalent and nonuniform PM models, the magnetic flux density distributions in both models are approximately identical. Based on this approximation, an analytical nonuniform PM model is established for fast estimation of the GBD PM demagnetization coefficient $\eta_{\text{non}}(x, y)$. Taking the estimation of $\eta_{\text{non}}(x, y)$ in layer 5 of the nonuniform PM model as an example, the procedure is illustrated in Fig. 3: Based on the direct calculation results of $\eta_{\text{hom}}(x, y)$ in FEM, the remanence of the homogeneous model (denoted as $B'_{r,\text{hom}}(x, y)$) can be derived with (1). Then, the recoil line of the homogeneous equivalent PM model can be obtained. The lowest magnetic flux density in magnetization direction $B_{n,\text{min}}(x, y)$ can be determined with the intersection between the recoil line and the demagnetization curve of the homogeneous model. Due to the magnetic flux density consistency in both PM models, the recoil line of the analytical nonuniform PM can be estimated with $B_{n,\text{min}}(x, y)$

and the demagnetization curve of the corresponding layer. The remanence of the nonuniform PM (named as $B'_{r,\text{non}}(x, y)$), and therefore $\eta_{\text{non}}(x, y)$, can be estimated.

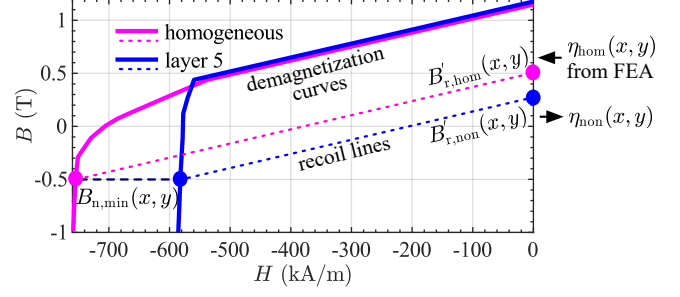


Fig. 3. Estimation procedure of $\eta_{\text{non}}(x, y)$ in layer 5 with $\eta_{\text{hom}}(x, y)$.

To validate the accuracy of the proposed method, a demagnetization current (3×rated) is injected into the unit machine. FEM model, using homogeneous and nonuniform PM model, yields $\eta_{\text{hom}}(x, y)$ and $\eta_{\text{non}}(x, y)$ in Figs. 4(a)-(b). The proposed analytical method is also conducted to estimate $\eta_{\text{non}}(x, y)$ as shown in Fig. 4(c). Notably, $\eta_{\text{hom}}(x, y)$ exhibits significant discrepancies, whereas $\eta_{\text{non}}(x, y)$ by the proposed method (calculation time 146s) and direct FEM (calculation time 218s) demonstrate strong consistency.

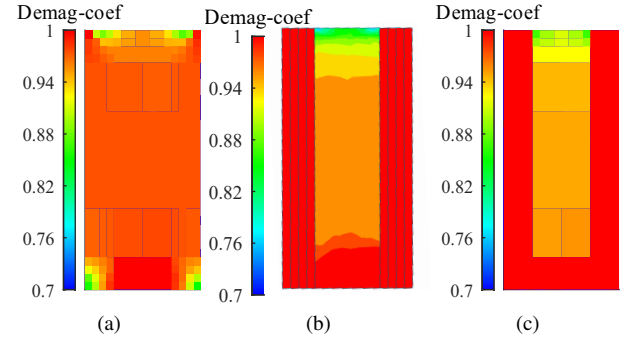


Fig. 4. Demagnetization coefficient results. (a) $\eta_{\text{hom}}(x, y)$ with FEM. (b) $\eta_{\text{non}}(x, y)$ with FEM. (c) $\eta_{\text{non}}(x, y)$ with analytical model.

In summary, the proposed method, integrated with the homogeneous equivalent PM model in FEM for machine electromagnetic performance and the analytical nonuniform model for anti-demagnetization analysis, maintains high accuracy with the merit of computation efficiency.

IV. ACKNOWLEDGMENT

This work was supported by the National Key R&D Program of China (2022YFB3403100).

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