

Nonlinear Modeling and Analysis of Low-Coercive-Force PM in Variable Flux Memory Machine

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Variable flux memory machines (VFMMs) embrace the benefits of air-gap magnetic flux being adjusted with minimal loss, which is credited to the utilization of low coercivity force permanent magnets (LCF PMs), as it can be manipulated magnetization states (MSs) to either re-magnetize or de-magnetize by applying d-axis pulse currents. However, to quickly analyze the characteristics of VFMMs by the analytical method, the finite element method (FEM) is needed to obtain the specific parameters under different MSs, such as magneto-motive force (MMF) and magnetic reluctance, which significantly increases the complexity of the analysis process. Therefore, this paper first elaborates the MSs adjustment mechanism through a nonlinearity-involved parallelogram hysteresis model (NIPHM), and derives a function related to relative permeability versus magnetic field changes. Further, the magnetic circuit model of LCF PMs is improved through a nonlinear function linking μ_r and pulse current. The developed nonlinear magnetic circuit model of LCF PMs is then integrated into the equivalent magnetic circuit (EMC) model of a dual-layer VFMM. Consequently, the analytical predictions are obtained and compared with FEM results to validate the effectiveness of the proposed LCF PM model. The detailed model description and experimental validation will be provided in the full paper.

Index Terms—Equivalent magnetic circuit model, low-coercivity-force permanent magnets, magnetic reluctance, variable flux memory machine.

I. INTRODUCTION

COMPARED to traditional permanent magnet synchronous machines (PMSMs), variable flux memory machines (VFMMs) can realize a wider constant-power range by adjusting the magnetization states (MSs) of low-coercivity-force (LCF) PMs through d -axis pulse currents with minimal losses [1]–[2]. It is relatively computationally complicated to precisely predict specific MSs of LCF PMs in VFMMs, due to the need to combine finite element method with a numerical hysteresis model in the analysis process. Besides, this methodology normally fails to facilitate the initial design process and not intuitive for understanding how VFMMs work. Indeed, the equivalent magnetic circuit (EMC) method is widely recognized as a common solution for facilitating the initial design stage and explaining the operation mechanism of PM machines. But the hysteresis model of LCF PMs is highly nonlinear unlike the high-coercivity-force (HCF) PMs, such as NdFeB, which complicates its modeling process of magneto-motive-force (MMF) and magnetic reluctance. Thus, accurate calculation of LCF PMs at various MSs is a challenging and critical point for the initial design and analysis of VFMMs.

This paper proposes a new nonlinear model of LCF PM to accurately calculate the MMF and magnetic reluctance of LCF PMs at various MSs, which is highly beneficial for the initial design and analysis process of all kinds of VFMMs. By integrating the nonlinearity-involved parallelogram hysteresis model (NIPHM) [3] of LCF PMs, the function between the relative permeability μ_r of LCF PMs and the magnetic field strength H is obtained. Further, a nonlinear relationship between the magnetic reluctance of LCF PMs and the applied magnetizing current pulse I_m is established, which enables the EMC model to calculate MMF and magnetic reluctance of the LCF PMs at various MSs. Finally, the accuracy of the proposed model is verified by comparing the analytical results from this model with the prediction obtained from FEM. The proposed nonlinear EMC model of LCF PMs can significantly reduce the analytical complexity of VFMMs.

II. MODELING OF LCF PMs

A. Flux-Regulation Mechanism of LCF PMs

Unlike HCF PMs, which exhibit a linear hysteresis characteristic, LCF PMs feature a nonlinear hysteresis characteristic, leading to instability in MSs during operation. To better analyze the nonlinear variation of MSs, this paper adopts the NIPHM of positive magnetic induction intensity B , as shown in Fig. 1. This model consists of a major loop, and several minor loops corresponding to different MSs. Different hysteresis loops share the same coercivity H_c , but possess different remanences B_{rk} .

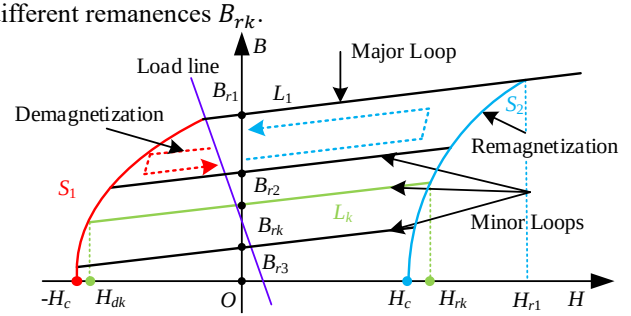


Fig. 1 NIPHM of LCF PMs

Among the several minor hysteresis loops, line L_k on top of minor loops which indicates different MSs can be expressed as:

$$B = \mu_0 \mu_r H \pm B_{rk}, k = 1, 2, 3 \dots \quad (1)$$

where μ_0 is the vacuum permeability, B on line S_1 and S_2 can be obtained by:

$$B = \frac{\mu_0 \mu_r H_{r1} + B_{r1}}{H_{r1} - H_c} (H \pm H_c) \quad (2)$$

As can be visualized from the NIPHM in Fig. 1, μ_r of the LCF PMs is not a constant, and it changes nonlinearly along S_1 and S_2 during magnetization. The nonlinear function between μ_{rk} and H_{rk} can be obtained through curve fitting S_2 :

$$\mu_{rk}(H_{rk}) = \mu_{r1} / (1 + e^{-\alpha(H_{rk} - \frac{H_c - H_{r1}}{2})}) \quad (3)$$

where μ_{r1} represents the relative permeability of LCF PMs

when fully magnetized, α can be determined by fitting experimental hysteresis data of specific LCF PMs.

B. Modeling of MMF and magnetic reluctance of LCF PMs

The magnetic circuit of VFMMs can be simplified as Fig. 2, in which the EMC model of LCF PMs comprises two components: equivalent MMF F_L and magnetic reluctance $R_L(I_m)$. The armature winding and HCF PMs is neglected to calculate the pulse magnetization flux $\Phi_I = N_c I_m$ more conveniently. The MMF of LCF PMs $F_L = H_c l_m$ remains constant at various MSs, where l_m is the thickness of LCF PMs, and $R_L(I_m)$ is used to equally reflect the change of MMF.

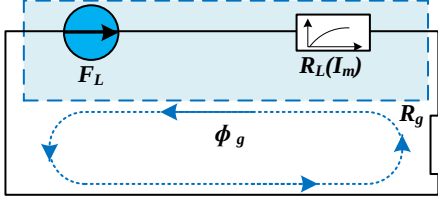


Fig. 2 The simple magnetic circuit of VFMMs

Typically, LCF PMs achieve fully magnetized with I_m that is twice I_N . Therefore when $I_m = 2I_N$, the pulse magnetic field intensity produced by I_m can be determined as H_{r1} , thereby the function between $\mu_{rk}(H_{rk})$ and I_m can be obtained:

$$\mu_{rk}(H_{rk}) = \frac{\mu_{r1}}{1 + e^{-\alpha \left(\frac{N_c I_m R_g}{l} - \frac{H_c}{2} + \frac{N_c I_N R_g}{l} \right)}} \quad (4)$$

where N_c and l is the number of turns and the length of armature winding. R_g is the magnetic reluctance of air gap. By utilizing the nonlinear EMC model of LCF PMs, the magnetic reluctance and MMF of LCF PMs at different MSs can be directly calculated without FEM, thereby simplifying the analytical process.

III. APPLICATION AND VALIDATION OF THE PROPOSED NONLINEAR MODEL

A dual-layer VFMM (DL-VFMM) incorporated with a combination of LCF PMs and HCF PMs is adopted as an example in this study. The topology of the investigated DL-VFMM and its corresponding EMC model are illustrated in Fig. 3, in which HCF PMs and LCF PMs are indicated with the subscripts: "H" and "L", respectively. R_b represents the magnetic reluctance of the flux bypass on the rotor. To verify the accuracy of this function, FEM with the frozen permeability (FP) method is adopted in the analysis of the DL-VFMM, which can eliminate the MMFs of the armature current and HCF PMs[4]. And the nonlinear function between I_m and B_g independent of the MMFs of the armature current and HCF PMs can be obtained through Fig. 3 (b) with the EMC model of LCF PMs as:

$$B_g = \frac{\Phi_m}{S_g} = \frac{F_L}{S_g} / \left(\frac{(R_g + R_H)R_b}{R_g + R_H + R_b} + R_L(I_m) \right) \quad (5)$$

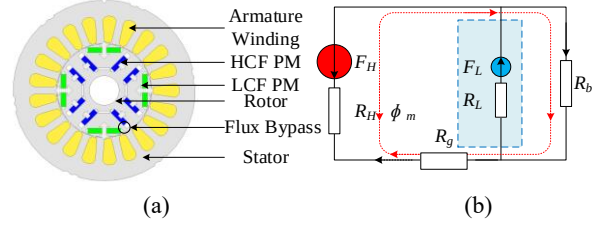


Fig. 3 (a) DLFMM topology; (b) Equivalent magnetic circuit model

The experimental hysteresis data of the LCF PMs employed in the DL-VFMM are curve fitted to determine the parameter α , μ_{r1} , H_c and H_{r1} [5], and then the curve between I_m and B_g is obtained through (5). It can be clearly seen from Fig. 4 that, the nonlinear function can accurately capture the change of MSs, which shows a nonlinear trend. Therefore, the effectiveness and accuracy of the proposed EMC model have been validated.

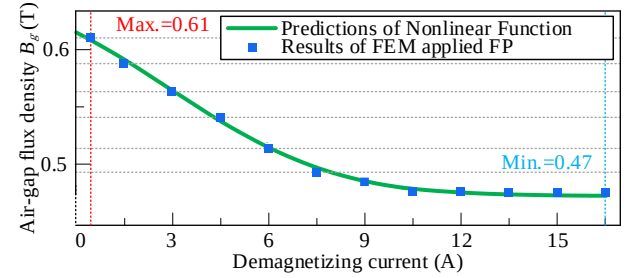


Fig. 4 Curves obtained from the magnetic circuit model and results from FEM

IV. CONCLUSIONS

In this paper, a new nonlinear EMC model of LCF PMs is proposed to accurately predict the MMF and magnetic reluctance at various MSs. The mechanism underlying the alteration of MSs in LCF PMs is explored through the NIPHM, which yields a nonlinear function between the relative permeability μ_{rk} and the magnetic field strength H_{rk} . By converting the nonlinear function into I_m and μ_{rk} , the nonlinear EMC model for any LCF PMs has been developed. The application in a DL-VFMM demonstrates that the nonlinear model of LCF PMs proposed can simplify the calculations of various VFMMs while maintaining a certain level of accuracy.

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