Effects of Magnetization State Variation on Variable-Leakage-Flux Property in Hybrid-Variable-Flux PM Machine

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This paper investigates the effect of magnetization state (MS) variation on the variable-leakage-flux (VLF) property in a newly developed hybrid-variable-flux permanent magnet machine (HVF-PMM) by adopting a coupled solution model (CSM), which combines the frozen-permeability method (FPM) with a nonlinear hysteresis model for low coercive force (LCF) magnets. By employing the CSM, the PM flux linkage at different MSs is separated from the main magnetic flux linkage, and the VLF characteristic under different MSs can be obtained and analyzed. On the other hand, the individual impact of different magnets on the magnetic saturation of the leakage flux bypass can be thoroughly analyzed, considering the interacting influence between the two types of magnets. In this case, the effect of MS variation on the VLF property can be accurately predicted, thereby offering the possibility for optimizing the trade-off between torque capability and flux regulation range. Finally, a prototype is experimentally validated to verify the theoretical analysis.

***Index Terms*—Flux regulation, frozen permeability, hybrid-variable-flux, memory machine, variable leakage flux.**

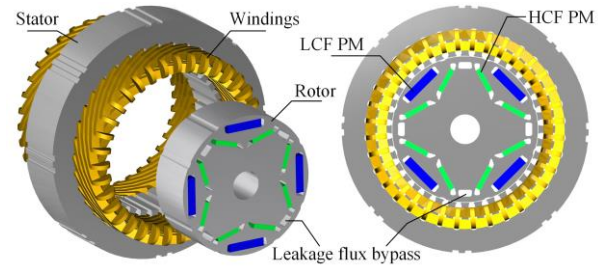
I. Introduction

RECENTLY, variable flux machines (VFM) [1]-[4] have attracted significant attention due to their superior speed regulation range and improved global efficiency. However, VFMs with a single-variable-flux unit face several challenges, such as additional field windings in hybrid-excitation machines or extra devices in mechanical flux-adjusting machines, both of which increase the complexity of the machine system. In particular, memory machines (MM) and variable leakage flux machines (VLFM), with reliable structure and convenient control, have emerged as promising candidates for wide-speed-range applications [2]-[3]. On the one hand, the magnetization state (MS) of low coercive force (LCF) magnets can be altered by applying a current pulse to realize flux regulation (FR). However, the usage of both high coercive force (HCF) and LCF magnets complicates achieving a balanced trade-off between torque density and FR capability within the limited rotor space. On the other hand, in VLFMs, the presence of leakage flux bypass will lead to compromised torque density. To address these issues, a hybrid-variable-flux PM machine (HVF-PMM) [2] has gained increasing attention due to its simple rotor design and improved FR capability. Notably, this machine integrates both variable MS and VLF properties, which means that the VLF method can expand the speed range for each MS, making it desirable and competitive for wide-speed-range applications. Nevertheless, although previous studies have shown that both variable-flux methods can enhance the FR capability [2]-[4], few in-depth investigations have been conducted on how the MS variation of LCF magnets affects VLF behavior.

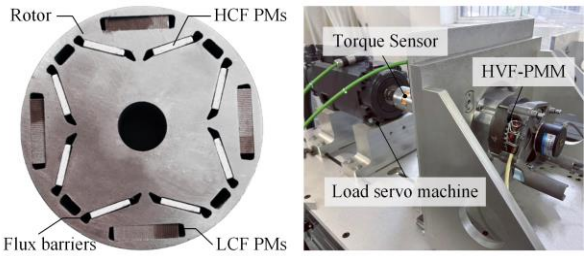
To address the foregoing issue, this paper aims to investigate the effect of MS variation on VLF property in a hybrid-variable-flux PM machine (HVF-PMM), with a coupled solution model (CSM) to reveal the underlying relationship between the MS variation of LCF magnets and VLF property. The proposed CSM integrates the frozen-permeability method (FEM) with a nonlinear hysteresis model for LCF magnets. In this case, the effect of MS variation on the VLF property can be accurately predicted, providing the possibility to optimize the trade-off between torque density and FR capability. Finally, a prototype is experimentally validated to verify the theoretical analysis.

II. Description of Investigated HVF-PMM

The topology and prototype of the investigated HVF-PMM are shown in Figs. 1(a) and (b), respectively. The HVF-PMM is characterized by a delta-type PM structure, consisting of HCF and LCF magnets. The MSs of the LCF magnets can be altered by applying re-/demagnetizing current pulse, enabling FR capability. Besides, a leakage flux bypass is designed between adjacent magnetic poles, thereby introducing a VLF property. Hence, two distinct variable-flux units are effectively integrated. Typically, the "flux-enhanced" or "flux-weakened" states arise when the LCF magnets are magnetized in the same or opposite directions to the HCF magnets, thereby either enhancing or weakening the air-gap flux.



(a)



(b)

Fig. 1. Topology and prototype of HVF-PMM. (a) 3-D view. (b) Prototype.

III. Operating Principle of The HVF-PMM

To effectively illustrate the MS variation of the investigated HVF-PMM design, Fig. 2 presents a simplified schematic of its FR behavior, presenting the VLF property under various MSs. The PM flux in HVF-PMM can be regulated by two variable-flux methods, providing high flexibility in FR. The MS of the LCF magnets can be dynamically varied by applying a re-/demagnetizing current pulse, which can weaken the main magnetic flux and thus broaden the speed range. Furthermore, under specific MSs, the VLF property can increase the leakage flux at light load conditions. Notably, the increase in leakage flux will reduce the effective flux entering the stator, thereby lowering iron losses and improving overall efficiency.

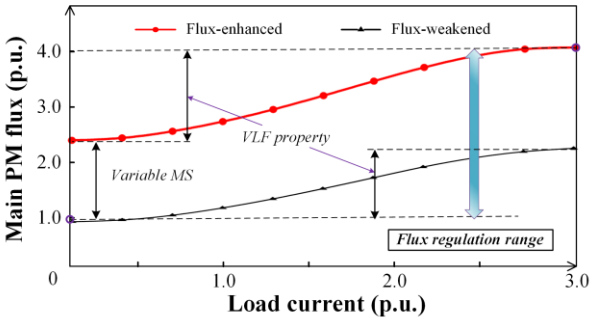


Fig. 2. Schematic diagram of the HVF behavior.

Typically, the FR range represents the overall variation in the PM flux, which is contributed by the two variable-flux units. In particular, the VLF property is realized by altering the magnetic saturation degree of the leakage flux bypass by the armature magnetic field. However, the magnetic saturation of the leakage flux bypass can also be influenced by the MS variation of the LCF magnets, causing the VLF property to change accordingly. In addition, the HCF and LCF magnets are arranged in series in space, their interaction relationship also indirectly influences the VLF property. Therefore, it is crucial to figure out the effect of MS variation on VLF property to achieve a more balanced design of the two variable-flux units, thereby optimizing the trade-off between torque density and FR capability.

IV. Investigation of MS Variation on VLF Property

Fig. 3 shows the flowchart of the CSM, which combines the frozen-permeability method (FEM) with a nonlinear hysteresis model for LCF magnets. By adopting the proposed method, the PM flux linkage can be separated from the main magnetic flux linkage, thereby enabling the calculation of the PM flux in HVF-PMM. Besides, Fig. 4 presents the relative permeability distributions under both flux-enhanced and flux-weakened states. It can be found that the magnetic field distributions differ under various MSs, particularly with variations in the relative permeability of the leakage flux bypass, which confirms its FR capability and the effect of MS variation on VLF property. Furthermore, Fig. 5 illustrates the VLF property under flux-enhanced and flux-weakened states, with VLF ranges of 25.2% and 11.3%, respectively. The results also demonstrate that the VLF properties vary with different MSs, highlighting the underlying coupling relationship between the two variable-flux units. More in-depth analysis and evaluation of the effect of MS variation on the VLF property in HVF-PMM, along with experimental validation, will be presented in the full paper.

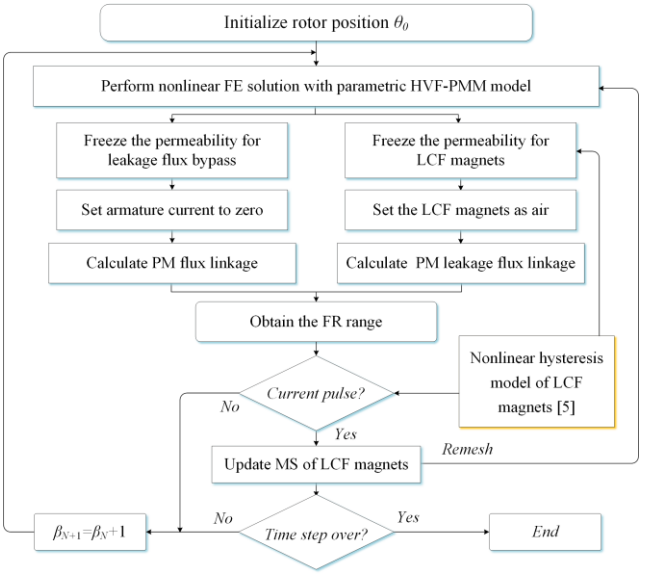
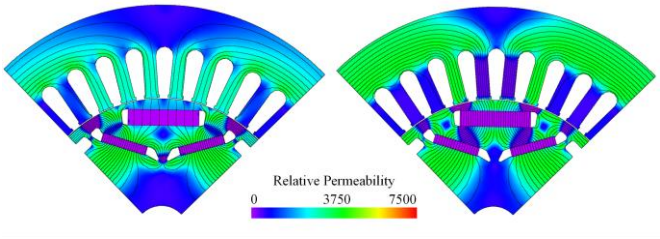
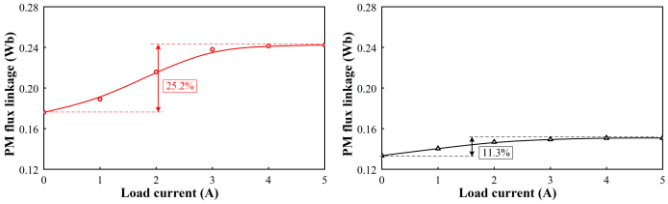


Fig. 3. Flowchart of the proposed CSM.



(a) (b)

Fig. 4. Relative permeability distributions under different MSs. (a) Flux-enhanced. (b) Flux-weakened.



(a) (b)

Fig. 5. VLF property under different MSs. (a) Flux-enhanced. (b) Flux-weakened.

References

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