

A Novel Dual-Layer Asymmetric Series-Magnetic-Circuit Variable Flux Memory Machine

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This paper proposes a novel dual-layer asymmetric series-magnetic-circuit variable flux memory machine (ASMC-VFMM), which combines the series-magnetic-circuit (SMC) structure and the asymmetric permanent magnet (APM) design in an integrated form. Additionally, the use of APM arrangement in the rotor introduces a magnetic-field-shifting (MFS) effect, which effectively addresses the issue of insufficient output torque under the flux-weakened state. Furthermore, the low coercive force (LCF) magnet is adopted in the first PM layer to expand the high-efficiency speed range and the flux changeable (FC) range of the machine. Firstly, the evolution and machine topology of the ASMC-VFMM are introduced. Then, the electromagnetic performance analysis of the proposed machine is conducted using finite element analysis (FEA). Besides, the torque performance of the proposed machine is also compared with a conventional symmetrical SMC-VFMM. The analysis reveals that the proposed machine has a broad FC range and good torque capability under the flux-weakened state.

Index Terms—Asymmetric permanent magnet (APM); low coercive force (LCF) PM; magnetic-field-shifting (MFS) effect; variable flux memory machine (VFMM).

I. INTRODUCTION

In recent years, variable flux memory machines (VFMMs) have garnered widespread attention due to their unique magnetization characteristics [1]–[2]. However, traditional VFMMs still face several issues in practical applications. For example, its potential for high efficiency operation is limited by the narrow flux changeable (FC) range. Moreover, the output torque of the VFMM is insufficient under the flux-weakened state, which further hinders its promotion in high-speed and high-torque applications.

To address these problems, various improvements of the VFMM have been proposed in the academic community, including optimizing permanent magnet (PM) configurations and improving magnetic circuit designs [3]. However, these methods normally struggle to simultaneously enhance both the FC range and the torque performance under the flux-weakened state.

To overcome this technical bottleneck, a novel dual-layer asymmetric series-magnetic-circuit variable flux memory machine (ASMC-VFMM) is proposed in this paper. This design combines the dual-layer series-magnetic-circuit (SMC) VFMM with the asymmetric-PM VFMM. The main contributions of this paper are as follows:

- 1) The torque performance of the machine under the flux-weakened state is effectively improved due to the existence of the magnetic-field-shifting (MFS) effect.
- 2) Due to the improved torque performance of the machine under the flux-weakened state, the high-efficiency operating range of the proposed machine is effectively extended.

First, the topology evolution process and the topology of the proposed ASMC-VFMM are described. Then, the electromagnetic performance of the proposed machine is thoroughly analyzed using finite element analysis (FEA). Furthermore, the torque performance of ASMC-VFMM is also compared with a conventional symmetrical SMC-VFMM.

II. MACHINE TOPOLOGY

Fig. 1 illustrates the topology evolution of the proposed ASMC-VFMM. The magnetic circuit of the proposed machine adopts the traditional SMC type. The low coercive force (LCF) PM in the first layer forms two series circuits with the two high coercive force (HCF) PMs in the second layer. The topology of the ASMC-VFMM is shown in Fig. 2. Moreover, the proposed machine employs an asymmetric design, which shifts the LCF PM and HCF PM2 perpendicular to the d -axis direction of the machine. The MFS effect is exhibited when the machine is under the flux-weakened state [4], which effectively enhances the torque capability of the machine under this state.

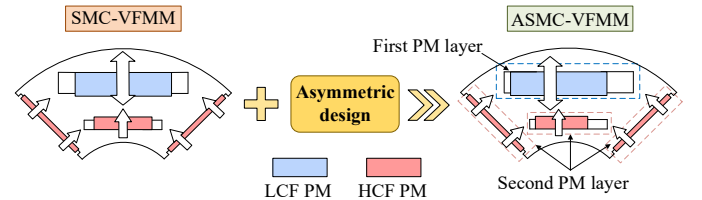


Fig. 1. The evolution of the rotor topology.

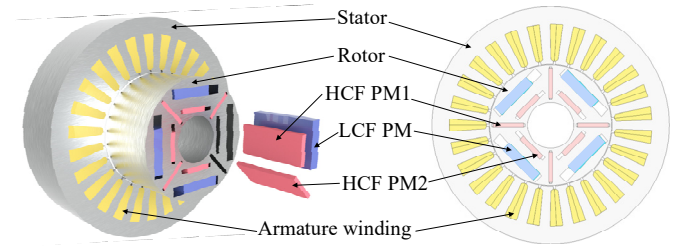


Fig. 2. Topology of the investigated ASMC-VFMM.

III. ELECTROMAGNETIC PERFORMANCE

A. FC Capability

Fig. 3 shows the magnetic field distributions of the machine under different magnetization states. It can be observed that the

air-gap flux of the proposed machine is significantly reduced under the flux-weakened state compared to the flux-enhanced state. Fig. 4 illustrates the no-load air-gap magnetic flux density waveform and harmonic spectra of the machine under two different states. The air-gap flux amplitude of the machine varies within a range of 2.2 times, which demonstrates the good FC capability of the proposed machine.

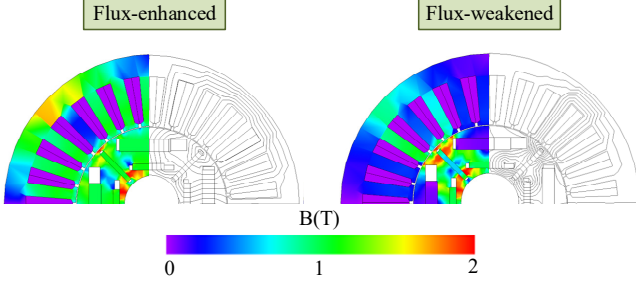


Fig. 3. The no-load magnetic field distributions of ASMC-VFMM.

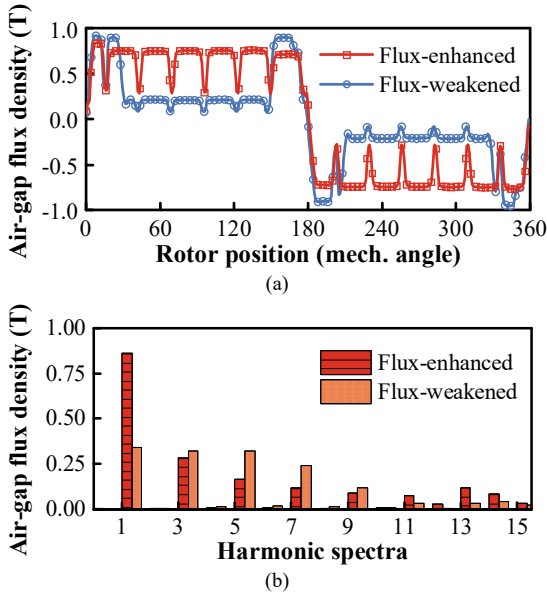


Fig. 4. No-load air-gap flux densities of ASMC-VFMM. (a) Waveforms. (b) Harmonic spectra.

B. Torque Performance

Fig. 5 shows the torque performance curve of the proposed ASMC-VFMM and SMC-VFMM. It can be observed that the ASMC-VFMM and SMC-VFMM achieve maximum output torque at 29° and 28° under the flux-weakened state. Moreover, the output torque of the ASMC-VFMM under the flux-weakened state is greater than that of the SMC-VFMM.

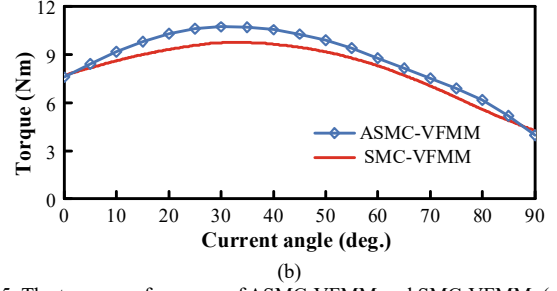
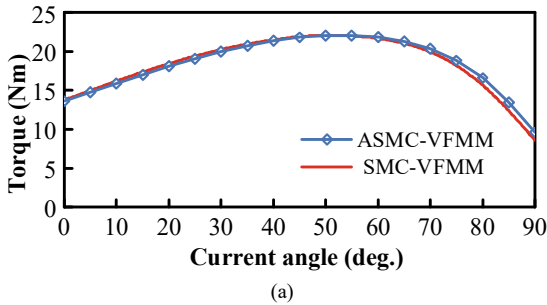


Fig. 5. The torque performance of ASMC-VFMM and SMC-VFMM. (a) Flux-enhanced state. (b) Flux-weakened state.

C. Efficiency Maps

Fig. 6 shows the efficiency maps of the proposed machine. The high-efficiency speed range of the machine under the flux-weakened state is effectively extended, with the high-efficiency (greater than 90% efficiency) speed range expanding from 4100 r/min to 7900 r/min.

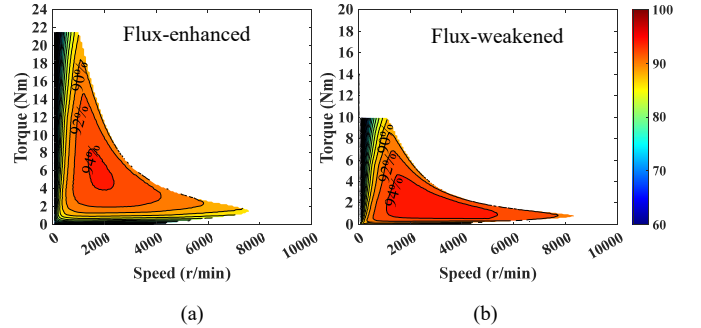


Fig. 6. Efficiency maps under the two different states. (a) Flux-enhanced state. (b) Flux-weakened state.

IV. CONCLUSION

A novel ASMC-VFMM is proposed in this paper, in which an asymmetric PM design is employed to enable that the machine exhibits MFS effects under the flux-weakened state to improve output torque capability. The results show that the proposed machine not only performs excellently in terms of FC range, but also demonstrates high output torque capability under the flux-weakened state. Besides, the high-efficiency speed range of the machine is effectively extended.

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