

A New Composite Multi-Magnetic Circuit Variable Flux Memory Machine with Low Magnetization Current Requirements

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The required magnetization current for variable flux memory machines (VFMMs) is typically several or even tens of times the load current, which severely limits their potential for high-speed efficiency improvement. To address this issue, this paper proposes a novel composite multi-magnetic circuit VFMM (CMMC-VFMM), where the maximum magnetization current is capped at the on-load current. By employing distinct series magnetic circuit arrangements on both dq -axes, the proposed machine ensures stable operation points of low coercive force (LCF) magnets. Additionally, the high coercive force (HCF) magnet on the d -axis and the LCF magnet on the q -axis can form two parallel magnetic circuits, thereby enhancing its flux-adjusting (FA) capability. Furthermore, the proposed machine not only inherits the advantages of various magnetic circuit configurations but also substantially reduces the magnetization current requirements by utilizing more magnetic circuits. The results indicate that the proposed CMMC-VFMM can achieve a wide FA range, which results in notable efficiency improvement at the high-speed region, even under the constraints of the low magnetization current.

Index Terms—Composite multi-magnetic circuit (CMMC); flux-adjusting (FA) capability; variable flux memory machine(VFMM).

I. INTRODUCTION

PERMANENT magnet (PM) machines are extensively utilized in industrial applications due to their simple structure and high torque density. Traditional PM machines generally employ high coercive force (HCF) magnets, which have a relatively stable magnetic flux [1]. Nevertheless, during high-speed operation, the magnetic flux of the machine needs to be reduced using flux-weakening current, which results in low efficiency in the high-speed region.

To address these issues, variable flux memory machines (VFMMs) [2] are developed, utilizing low coercive force (LCF) PM magnets for magnetic flux regulation. However, compared to HCF magnets, LCF magnets have lower magnetic energy products. This also means that the VFMM utilizing solely LCF magnets exhibits suboptimal torque. To tackle these issues, hybrid PM designs utilizing both different coercivity magnets are proposed [3]. By placing two different types of magnets in parallel [4], the magnetic fluxes from the LCF magnets can be effectively short-circuited by the HCF magnets, bestowing upon the outstanding flux-adjusting (FA) capability of VFMM. Nonetheless, LCF magnets configured in parallel are prone to demagnetization due to the influence of load current. Conversely, series magnetic circuit arrangement demonstrates improved demagnetization resistance (DR) capability, albeit with a limited FA range. Thus, a composite structure merging series and parallel magnetic circuits is developed to balance the FA and DR capabilities. Nonetheless, the current composite structures exhibit limited magnetic circuit numbers, making it challenging to effectively reduce magnetic fluxes under weakened-flux state. Additionally, the excessive series of HCF magnets exacerbates the demagnetization difficulty of LCF magnets. As a result, the magnetization currents of the existing VFMMs are typically several to tens of times the load current.

To resolve this problem, this paper proposes a novel composite multi-magnetic circuit VFMM (CMMC-VFMM). It should be noted that the maximum magnetization current equals

the on-load current of the machine. The proposed machine can form multiple series magnetic circuits on both dq -axes, ensuring the DR capability under the load condition. Furthermore, the HCF magnets on the d -axis and the LCF magnets on the q -axis can create two parallel magnetic circuits, enhancing the FA capability of the machine. Compared with traditional composite structures, the proposed machine can achieve a significant reduction in magnetization current by utilizing its CMMC characteristics.

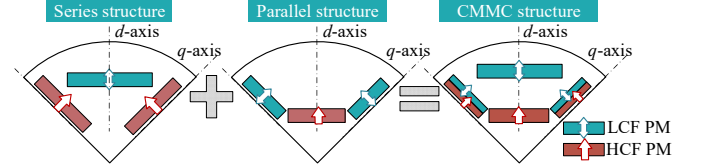


Fig. 1. Topological evolution of the CMMC-VFMM.

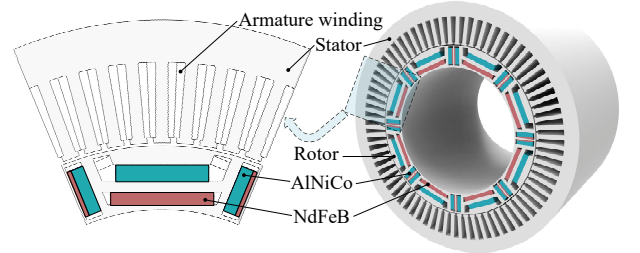


Fig. 2. Configuration of the CMMC-VFMM.

II. MACHINE TOPOLOGY

The topology evolution of the proposed CMMC-VFMM is illustrated in Fig. 1, which integrates both traditional series and parallel configurations. The proposed machine can possess two distinct types of magnets on the dq -axes simultaneously. In contrast, conventional structures typically feature a single type of magnet on these axes. The HCF magnet on the q -axis, along with the LCF magnets on the dq -axes, can form various serial magnetic circuits. Additionally, the HCF magnet on the d -axis not only forms a serial magnetic circuit with the LCF magnet on the d -axis but also creates two parallel magnetic circuits with the adjacent LCF magnets on the q -axis. The CMMC

characteristic of the proposed machine significantly reduces its magnetization current requirement. Furthermore, Fig. 2 shows the structure of the proposed CMMC-VFMM, employing the 72-slot 8-pole winding configuration.

III. ELECTROMAGNETIC CHARACTERISTICS

The magnetic field distributions of CMMC-VFMM at different states are shown in Fig. 3, where the maximum magnetization current equals the on-load current of the machine. The magnetic field of the proposed machine significantly decreases under the weakened-flux state compared to the enhanced-flux state. Additionally, the air gap flux density of the proposed machine is depicted in Fig. 4. By adjusting the magnetization state, the proposed machine enables a 1.5-fold amplitude variation of the air-gap flux density. Additionally, the torque characteristics of the proposed machine are illustrated in Fig. 5. The proposed machine achieves its maximum torque at 40° under the enhanced-flux state and 45° under the weakened-flux state. Due to the decrease in air gap flux density, the output torque of the machine under the weakened-flux state is lower than that under the enhanced-flux state.

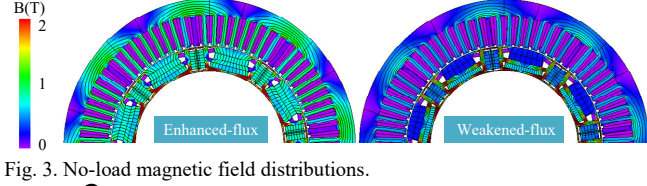


Fig. 3. No-load magnetic field distributions.

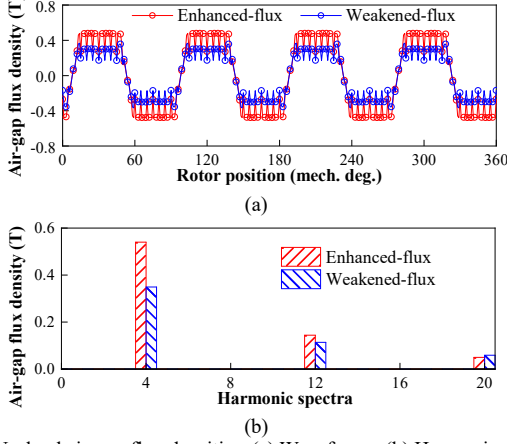


Fig. 4. No-load air-gap flux densities. (a) Waveforms. (b) Harmonic spectra.

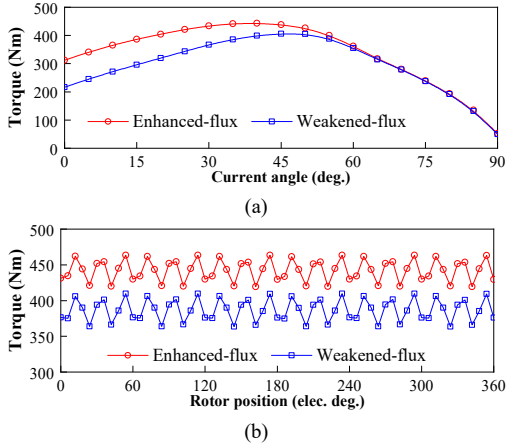


Fig. 5. Torque performance. (a) Torque-angle waveforms. (b) Maximum torque.

Furthermore, Fig. 6 illustrates the efficiency characteristics of the proposed CMMC-VFMM. The integrated efficiency map is based on selecting the high-efficiency points at the same speed and torque conditions. It is evident that the enhanced-flux state predominantly occurs in the high torque region, whereas the weakened-flux state is primarily located in the low torque region. Moreover, the efficiency in the high-speed range under the weakened-flux state exhibits a significant improvement compared to that under the enhanced-flux state, especially under ultra-high speed and low torque conditions.

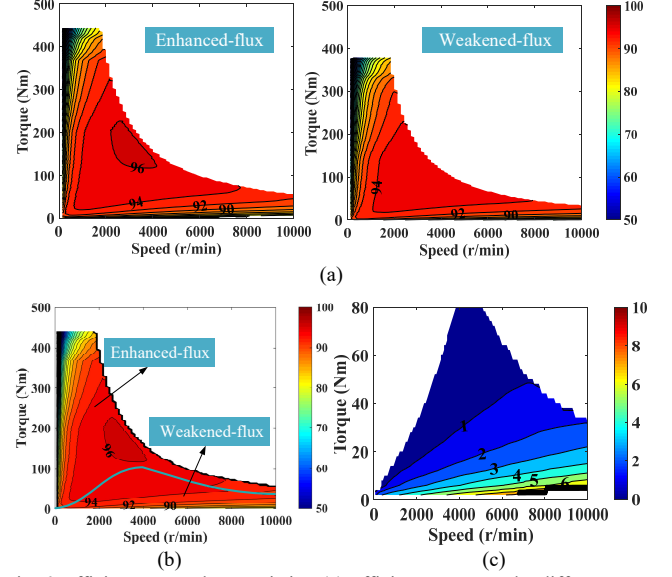


Fig. 6. Efficiency map characteristics. (a) Efficiency maps under different MSs. (b) Integrated efficiency map. (c) Efficiency enhancement of weakened-flux state relative to the enhanced-flux state.

IV. CONCLUSION

This article proposes a novel CMMC-VFMM, which employs multiple magnetic circuits positioned on the dq -axes. The proposed machine can combine the DR capability of series magnetic circuits and the wide FA capability of parallel magnetic circuits. Additionally, the unique CMMC characteristics significantly alleviate the magnetization complexity of the proposed machine. The results indicate that the proposed machine can achieve an FA range of 1.5-fold when the peak magnetization current is limited to the load current level. Crucially, the efficiency in the high-speed region under the weakened-flux state shows a marked enhancement relative to the enhanced-flux state, particularly under ultra-high speed and low torque conditions.

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