

A New Heteropolar Series-Parallel Variable Flux Machine with LCF Magnets Playing Different Roles

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This paper proposes a new heteropolar series-parallel variable flux machine (HSP-VFM) employing the low coercive force (LCF) magnets to play different roles. The LCF magnets are arranged on the q -axis of the proposed machine to perform different functions, which can form either series or parallel magnetic circuits with adjacent high coercive force (HCF) magnets. In the proposed design, the series magnetic circuit ensures the stability of the LCF magnets, while the parallel magnetic circuit enhances the flux-adjusting (FA) capability. The topological evolution process and topology structure of the proposed machine are first introduced. Then, the no-load and on-load characteristics of the proposed machine are evaluated individually, confirming the considerable FA range and torque variation capability. Particularly, the efficiency characteristics of the machine are further evaluated, confirming that the proposed HSP-VFM can achieve overall high efficiency through magnetization state adjustment.

Index Terms—Flux-adjusting (FA) capability; low coercivity force (LCF) magnets; magnetic circuit; variable flux machine(VFM).

I. INTRODUCTION

DUE to their performance superiority in terms of high torque density, permanent magnet (PM) machines have become the core drive in industrial applications such as electric vehicles. Conventional PM machines typically feature high coercive force (HCF) PMs with relatively constant magnetic fluxes. However, it is necessary to apply the flux-weakening current to reduce its magnetic fluxes during high-speed operation, which leads to low efficiency in the high-speed region [1].

To tackle these concerns, variable flux machines (VFMs) are proposed, employing low coercive force (LCF) PM for adjusting their magnetic fluxes [2]. Nonetheless, the LCF PM possesses a lower magnetic energy product compared with the HCF PM, relying solely on LCF PM for field excitation diminishes the output torque of the VFM. To address these challenges, the hybrid magnet solution combining LCF PM and HCF PM is proposed [3]-[5]. When the two types of magnets are arranged in parallel, the fluxes of the LCF PMs are vulnerable to short-circuiting by the HCF PMs, thereby achieving the broad flux-adjusting (FA) capability [3]. However, the operating point of LCF PM in the parallel configuration is susceptible to disturbances from armature fluxes, potentially leading to demagnetization issues. On the other hand, the series magnetic circuit configuration demonstrates superior demagnetization resistance (DR) capability, while encountering the challenge of the narrow FA range [4]. Therefore, the series-parallel structure integrating both series and parallel magnetic circuits is proposed to achieve both FA and DR capability [5].

Nonetheless, the prevailing series-parallel structures typically entail intricate multi-layered magnet arrangements, which require the employment of different LCF PMs for constructing diverse magnetic circuit configurations. This design results in a more complex PM structure under each pole, making it difficult to realize a series-parallel configuration in a simple PM structure.

Therefore, this paper proposes a novel heteropolar series-parallel variable flux machine (HSP-VFM) that utilizes LCF

magnets to serve multiple functions. In the proposed design, LCF magnets are strategically placed along the q -axis to fulfill distinct roles, enabling them to establish either series or parallel magnetic circuits with adjacent HCF magnets. The most crucial aspect is that the proposed HSP-VFM enables the implementation of a series-parallel configuration within a simple PM arrangement, while simultaneously exhibiting excellent FA and DR capability.

II. MACHINE TOPOLOGY

Fig. 1 depicts the topological evolution process of the proposed HSP-VFM. The series-parallel structure under the heteropolar poles can be realized by sharing the same LCF PMs with the conventional series and transposed parallel magnetic circuits. This also means that the magnetic circuit types are different under neighboring poles, while there is only one type of magnetic circuit under each pole. Overall, the presence of the series magnetic circuit guarantees the DR capability, while the availability of the parallel magnetic circuit enhances the FA range of the VFM.

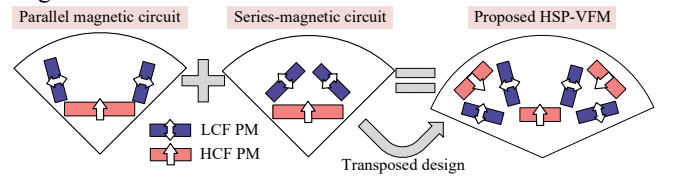


Fig. 1. Topological evolution process of the proposed HSP-VFM.

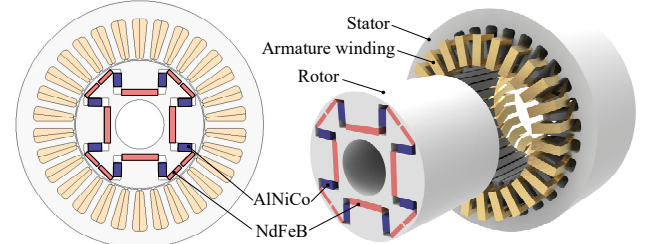


Fig. 2. Topology of the HSP-VFM.

The topology of the proposed HSP-VFM is plotted in Fig. 2. It can be seen that each pole of the PM can be regarded as a U-type PM with a relatively simple structure. The LCF PMs are

located in the q -axis, while the HCF PMs are located in the d -axis position close to the air gap side or the rotation shaft.

III. ELECTROMAGNETIC CHARACTERISTICS

Fig. 3 illustrates the magnetic field distribution of HSP-VFM at different magnetization states. There is a notable decrease in magnetic fluxes at the weakened-flux state compared with the enhanced-flux state, especially regarding the fluxes on the stator core. Additionally, Fig. 4 shows the air-gap flux density properties of the proposed machine. Altering the magnetization state leads to significant variations in air-gap flux density, with the fundamental amplitude of the air-gap flux density being particularly significant.

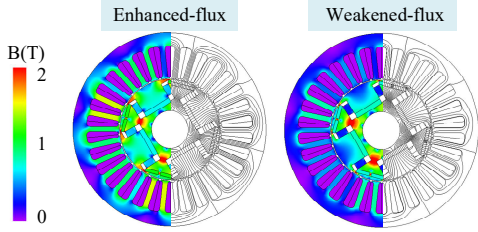


Fig. 3. No-load magnetic fields.

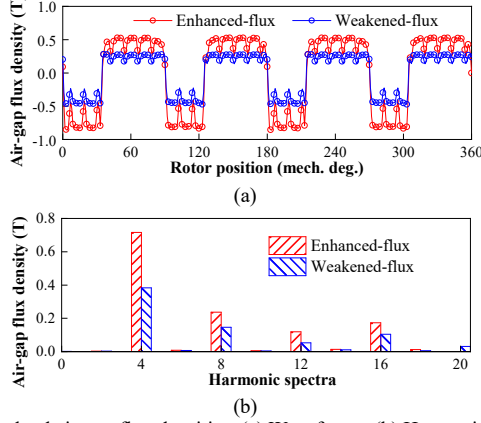


Fig. 4. No-load air-gap flux densities. (a) Waveforms. (b) Harmonic spectra.

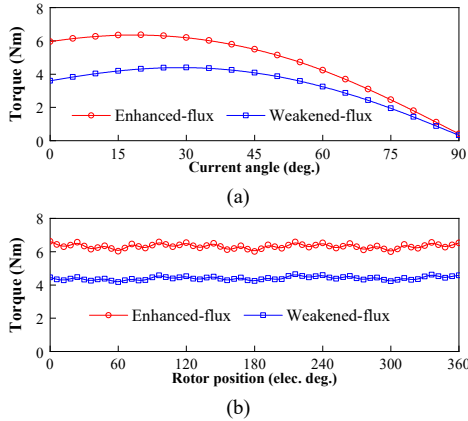


Fig. 5. Torque performance. (a) Torque-angle waveforms. (b) Peak torque.

Furthermore, the torque characteristics of the proposed machine are depicted in Fig. 5. The proposed machine can achieve maximum torque at 20° and 30° for the enhanced-flux and weakened-flux states, with output torques of 6.32Nm and 4.39Nm, respectively.

Besides, Fig. 6 plots the efficiency characteristics of the proposed machine. By adjusting the magnetization state, the

overall operating range of the machine state is significantly improved. Notably, at the weakened-flux state, the efficiency of the machine in the high-speed region is increased compared with the enhanced-flux state, extending the high efficiency ($>88\%$) range from 4000 r/min to 7000 r/min. Additionally, by integrating the efficiency across different magnetization states, the proposed HSP-VFM can achieve high efficiency throughout its entire operational range, with the enhanced-flux state suitable for low-speed regions and the weakened-flux state for high-speed regions.

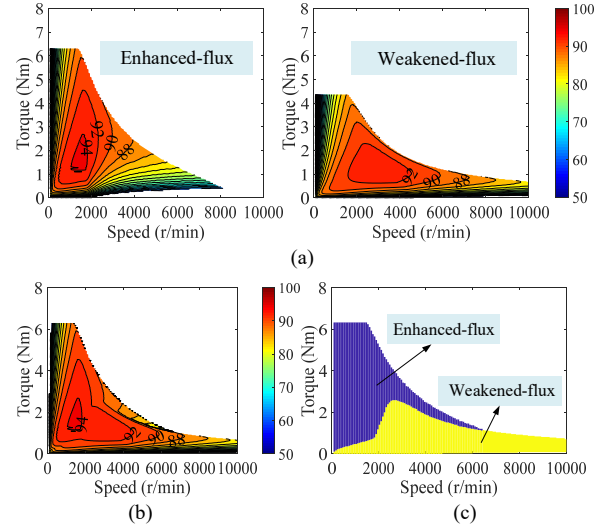


Fig. 6. Efficiency map characteristics. (a) Efficiency maps under different MSs. (b) Integrated efficiency map. (c) Distribution map.

IV. CONCLUSION

In this article, a new HSP-VFM utilizing the LCF magnets to play different roles is proposed. The LCF magnets are arranged on the q -axis to form either series or parallel magnetic circuits with adjacent HCF magnets. The proposed machine enables the implementation of a series-parallel configuration within a simple PM arrangement, while simultaneously exhibiting excellent FA and DR capability. The results show that the proposed machine can achieve significant changes in air-gap flux density. Besides, by adjusting the magnetization state, the overall operating range of the machine is significantly improved. Particularly, the high efficiency ($>88\%$) range can be extended from 4000r/min to 7000r/min at the weakened-flux state compared with that at the enhanced-flux state.

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