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Design and Analysis of a Dual-Stage Magnetic Geared Machine with Halbach Arrays

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Abstract: This paper presents the design and analysis of a Halbach dual-stage magnetic geared machine (Halbach-DS-MGM), which integrates a consequent-pole Vernier machine (CP-VM) and a coaxial magnetic gear (CMG) with Halbach arrays. The proposed structure addresses magnetic flux leakage and transmission ratio limitations in single-stage magnetic gears through a dual-stage transmission mechanism. By leveraging the unidirectional flux concentration effect of Halbach arrays, the stator yoke thickness is significantly reduced while achieving a total gear ratio of 29.45. Comparative analysis with a commercial mechanical planetary gear module reveals that the Halbach-DS-MGM achieves equivalent rated torque (10.2 Nm) while eliminating gear backlash.

Keywords: Magnetic gear (MG), Magnetic Geared Machine (MGM), two-stage transmission, Halbach Arrays.

1. Introduction

In many fields, magnetic gears (MGs) are regarded as the optimal alternative to mechanical gears. Compared to mechanical gears, the most distinguishing characteristic of MGs is their use of permanent magnets to achieve non-contact magnetic transmission.

For single-stage MGs, an excessively large transmission ratio can lead to severe magnetic flux leakage [1]. To address this issue and enhance the transmission ratio of MGs, a multi-stage transmission design proves effective. Baninajar et al. [2] demonstrated a 63.3:1 dual-stage coaxial magnetic gear (CMG) for marine hydrokinetic generators, which combines a 6.67:1 flux-concentrating inner rotor stage and a 9.5:1 Halbach-array-based stage, achieving an overall torque density of 228.6 Nm/L at 45 r/min. Qin et al. [3] proposed a load angle-based nonlinear dynamic analysis method for two-stage magnetic gearboxes in wind turbines. Filippini et al. [4] demonstrated that multistage CMGs — designed by embedding a secondary gear internally — enable transmission ratios comparable to multistage mechanical gearboxes. And the optimization further reveals that equal stage ratios maximize both efficiency and specific torque.

Magnetic Geared Machines (MGMs) can be derived from MGs [5]. In our previous work, a dual-stage Magnetic Geared Machine (DS-MGM) was proposed. The DS-MGM combines two stages of magnetic gearing into an integrated system: the first stage is a Vernier machine (VM), and the second stage is a magnetic gear [6]. Both stages share a common rotor. In [7], the operational principles of dual-stage transmission were analyzed, and revealed the impact of magnetic flux coupling on DS-MGM output torque. These studies highlighted that the single-pole permanent magnet on the MG side of the common rotor requires a relatively large size, leading to increased rotor yoke thickness due to magnetic flux coupling.

By leveraging the unidirectional flux concentration effect of Halbach arrays, the rotor can adopt a Halbach configuration, significantly reducing yoke thickness[8]. This design capitalizes on the Halbach arrays' ability to concentrate flux on one side of the rotor, enabling a compact structure without compromising magnetic field strength. This paper discusses a DS-MGM incorporating Halbach arrays (Halbach-DS-MGM). In Section II, the structure is discussed. In Section III, the characteristics are analyzed. In Section IV, a comparative analysis is conducted between the Halbach-DS-MGM and existing mechanical planetary gear machines.

2. Structure of Halbach-DS-MGM

Fig.1(a) and 1.(b) illustrate a mechanical planetary gear module, comprising an external permanent magnet (PM) machine and an internal planetary gear reducer. The PM machine rotor is rigidly connected to the sun gear of the reducer, forming a common rotor (Fig. 1(a)), while the stator of the outer PM machine is integrated with the ring gear, forming a common stator (Fig. 1(b)). The planetary gear serves as the output rotor.

Building on this configuration, the proposed Halbach-DS-MGM (Fig. 1(c)) employs a Consequent-Pole Vernier Machine (CP-VM) as the external PM machine and an internally integrated coaxial magnetic gear with Halbach arrays (Halbach-CMG). The CP-VM rotor and the Halbach-CMG high-speed rotor form a common rotor, while the CP-VM stator and Halbach-CMG outer rotor constitute a common stator. A non-magnetic aluminum spacer isolates the magnetic flux between the two stages. The flux-modulating ring (low-speed rotor) of the Halbach-CMG serves as the output rotor.

Key specifications of the Halbach-DS-MGM are listed in Table 1. The PM material is NdFeB35. The PM arc ratio of the CP-VM is optimized using the method introduced in [9]. The Halbach-DS-MGM achieves a total gear ratio of 29.45 through the CP-VM ratio (−31/5) and Halbach-CMG ratio (19/4).

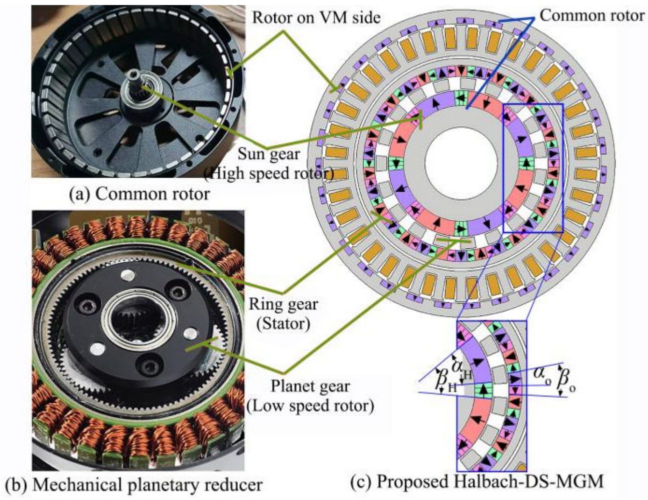


Figure 1. A Halbach-DS-MGM derived from existing mechanical planetary gear machine

Table 1. Specifications of Halbach-DS-MGM

CP-VM		Halbach-CMG	
Rotor pole pairs	31	Outer rotor (fixed) pole pairs	15
Stator slots	36	Flux-modulating ring segments	19
Stator pole pairs	5	High-speed rotor pole pairs	4
Rotor outer diameter / mm	111	Airgap length / mm	1
Rotor inner diameter / mm	101.2	Outer rotor PM thickness / mm	4
Stator outer diameter / mm	100	Outer rotor inner diameter / mm	63
Stator inner diameter / mm	78	Flux-modulating ring thickness / mm	3.9
Rotor PM thickness / mm	2	High-speed rotor PM thickness / mm	5
Rotor PM arc ratio	0.56	α_H/β_H	0.748
turns per slot	40	α_o/β_o	0.61
Axial length / mm			
Airgap length / mm			

Fig. 2 presents the flux lines and flux density distributions of the Halbach-DS-MGM. These results confirm a mechanically coupled yet magnetically decoupled structure.

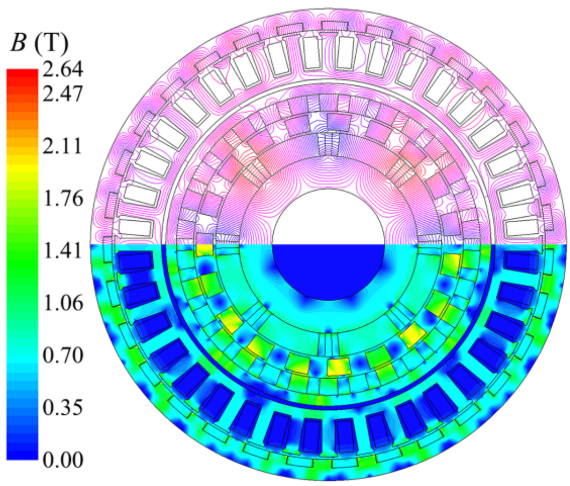


Figure 2. Flux lines and flux density distributions of the Halbach-DS-MGM

3. Characteristic Analysis of Halbach-DS-MGM

3.1. No-load Back-EMF

At a common rotor speed of 60×310/31 rpm, the output rotor speed is 60×310/(31×4.75) rpm. The no-load back-EMF waveform in Fig.3 exhibits an amplitude of 42.6 V.

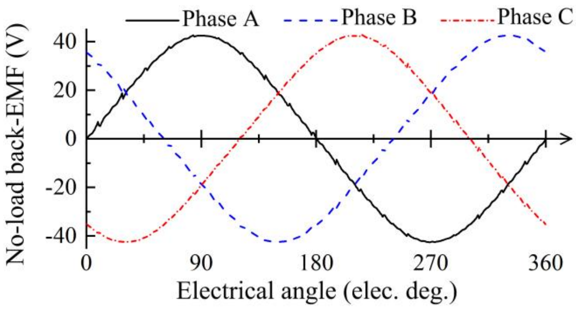


Figure 3. No-load back-EMF of the Halbach-DS-MGM

3.2. Torque Capability

The static torque characteristics of the Halbach-CMG are shown in Fig. 4. The common rotor allows a maximum input torque of 3.75 Nm, while the output rotor delivers 17.83 Nm. At an RMS current I_{rms}=2.9 A, the electromagnetic torque of CP-VM is 3.75 Nm. Output torque is adjustable via current regulation for I_{rms}<2.9 A.

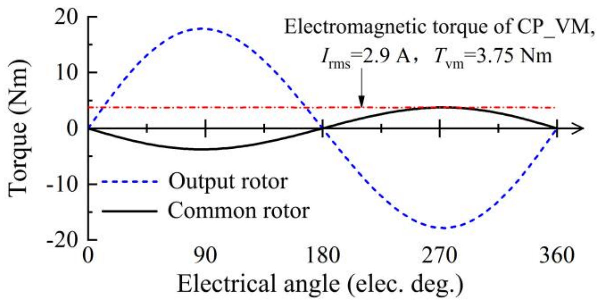


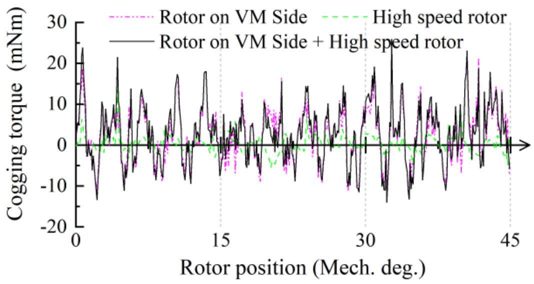
Figure 4. Static torque of the Halbach-DS-MGM

3.3. Cogging Torque

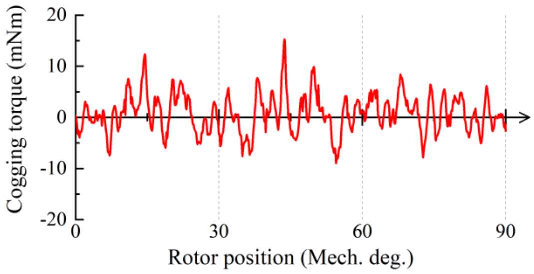
Magnetic decoupling between the CP-VM and Halbach-CMG minimizes cogging torque. As shown in Fig.5, under no-load conditions, the common rotor cogging torque remains below ±30 mNm, and the output rotor cogging torque is under ±15 mNm.

4. Comparison of Halbach-DS-MGM and Existing Mechanical Planetary Gear Machine

Table II compares the Halbach-DS-MGM with a commercial mechanical planetary gear module. While the Halbach-DS-MGM is larger in size, the rated torque achieve performance parity with the mechanical planetary gear module. However, its peak torque (17.83 Nm) is lower due to CMG limitations. Notably, the Halbach-DS-MGM eliminates gear backlash.



(a) Common rotor



(b) Output rotor

Figure 5. Cogging torque of the Halbach-DS-MGM

Table 2. Parameter comparision of Halbach-DS-MGM and Existing Planetary Reducer

	Mechanical planetary gear module [10] (Type: X8-20)	Halbach-DS-MGM
Dimensions (dia.×length)	89 mm×16 mm	110 mm×20 mm
Rated power / W	200	150
Rated voltage / V	48	48
Rated speed / rpm	190	126
Rated current / A	5.2	1.6
Rated torque / Nm	10	10.2
Peak Torque / Nm	20	17.83
Machine rotor pole pairs	20	31
Gear ratio of inner reducer	6	4.75
Gear backlash / Arc min	10	0

5. Conclusion

The Halbach-DS-MGM demonstrates a novel integration of a consequent-pole Vernier machine and a coaxial magnetic gear with Halbach arrays, addressing key limitations of single-stage magnetic gears. The dual-stage design achieves a total gear ratio of 29.45. Magnetic decoupling between stages minimizes cogging torque, with values below ±30 mNm (common rotor) and ±15 mNm (output rotor). The Halbach-DS-MGM delivers a rated torque of 10.2 Nm and speed of 126 rpm, matching commercial mechanical planetary gear module.

Acknowledgments

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