Electromagnetic Design of a New Dual-magnet Magnetic-geared Machine Using Parallelogram Hysteresis Model

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***Abstract*—This paper presents a new hybrid-structure machine, namely dual-magnet magnetic-geared machine, which artfully integrates the magnetic-gearing effect and the flux-mnemonic capability together. The key is to adopt the hybrid-structure with the flux-modulation ring, dual-magnet and magnetizing winding. In this way, the flux-modulation ring is able to modulate the high-speed rotating field of the armature winding field and the low-speed rotating field of the PM rotor. Meanwhile, the electromagnetic field which is generated by the dual-magnet of NdFeB PMs and AlNiCo PMs is able to be online tuned via the magnetizing winding.**

***Index Terms*—Dual-magnet, magnetic-geared machine, memory machine, hybrid-structure machine, flux control, hysteresis model.**

I. Introduction

Hybrid structure machine is few introduced and existed in literature report due to the seldom requirement in traditional industry. However, thanks to the fast development of sustainable energy conversion, electric machines are expected with the high-torque output and wide-speed operation in many occasions [1]. Magnetic-geared machines are a new type of machine, which is welcomed in recent research [2]-[3]. Since they offer the prominent merit of magnetic-gearing effect without involving mechanical contacts, they are highly promising for the high-torque direct-drive applications. However, their operating speed range is limited due to the difficulty in flux control. Another challenging new type is the flux-mnemonic PM machine, which is used the AlNiCo PM for generating the electromagnetic field [4]-[5]. So, it possesses the distinct merit of controllable magnetization, which is highly favorable for the wide-speed operation.

The purpose of this paper is to propose a new hybrid-structure machine, which is artfully to incorporate the abovementioned two virtues together with the magnetic-gearing effect and the flux-mnemonic capability. Namely, the so-called dual-magnet magnetic-geared (DMMG) machine, inherently achieves the expected features of high-torque output and wide-speed operation for sustainable energy conversion.

II. Machine Design

Fig. 1 shows the proposed machine configuration, which consists of an outer rotor, a modulation ring (MR) and an inner stator. The outer rotor has 16 pole-pair NdFeB PMs mounting on the inside surface. The static MR has 18 iron pieces sandwiched between the rotor and the stator. The stator accommodates two sets of windings (armature windings and magnetizing windings) and 3 pole-pair AlNiCo PMs. The magnetizing winding is used to properly magnetize or demagnetize the AlNiCo PM. Hence, this hybrid-structure machine offers the magnetic gearing effect to achieve the high torque output, and the flux-mnemonic capability to provide wide-speed operation.

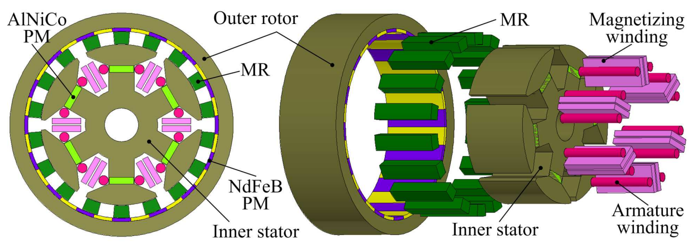

Fig. 1. Proposed DMMG machine.

Therefore, with the hybrid-structure of magnetic-gearing effect and the flux-mnemonic capability, the proposed DMMG machine achieves the following features and merits.

- The machine has a compact structure with fully utilizing the inner stator room for accommodating AlNiCo PMs, AC windings, and magnetizing windings.
- The outer-rotor topology inherently achieves the directly coupling capability for the rotating mechanical part, such as the wind blades and the EV tire rim.
- The machine inherits the magnetic-gearing effect, hence suitable for direct-drive operation. Also, its flux-mnemonic capability makes it suitable for speed extension.
- The machine implements two types of PMs and two sets of windings, hence able to offering the fault tolerant operation during one set of windings or PM fault.

III. Analysis Approach

The AlNiCo PM has different operating features from the NdFeB PM, due to their different demagnetization characteristics as shown in Fig. 2(a). Because of the nonlinear characteristics of the AlNiCo PM, it is difficult to analyze the proposed machine. For instance, when a demagnetization current pulse is applied, the operating point of the AlNiCo PM moves along the recoil line and settles at a lower magnetization level. So, a parallelogram hysteresis model is incorporated into the finite-element method [4]. As shown in Fig. 2(b) in which the major hysteresis loop and all minor hysteresis loops have the same value of coercivity, whereas they have different values of remanence. This model offers the piecewise-linear feature which can facilitate the implementation of time-stepping finite-element analysis.

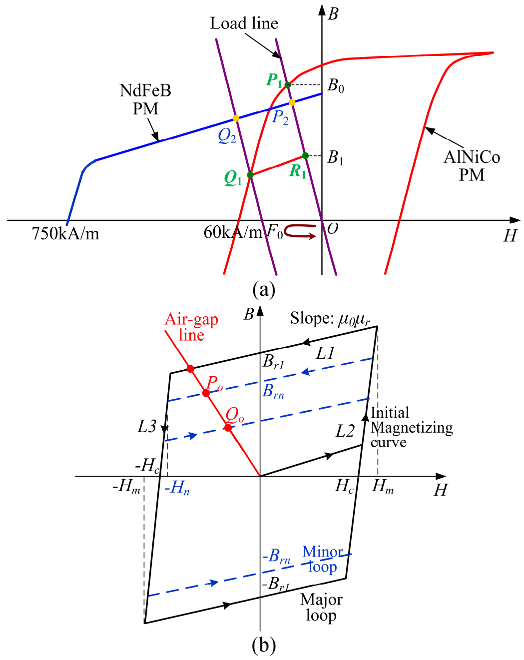

Fig. 2. Operating features of both types of PMs. (a) B-H curves. (b) Proposed parallelogram hysteresis model for AlNiCo PM.

IV. Performance Analysis

First, the high speed (1000rpm) operation performances of the proposed machine are calculated and discussed. Fig. 3 shows the machine flux linkages under different magnetizing levels of AlNiCo PM. It can be seen that the proposed machine has the different flux linkages under different magnetizing levels. Thus, it proves that the machine has the flux-mnemonic capability to offer the wide-speed operation.

Second, the low speed (250rpm) operation performances of the machine are analyzed. Fig. 4 is the torque-angle capabilities under different magnetizing levels of AlNiCo PM. It can be found that the proposed machine can provide the torque up to 50.2Nm, 38.3Nm, and 20.8Nm, with full-, half-, and zero-magnetizing level. Fig. 5 shows the steady torques under different magnetizing levels of AlNiCo PM. It can be found that the average steady torques are 48.4Nm, 35.7Nm, and 16.5Nm, respectively. Thus, it tells that the proposed machine can offer the high torque output at low-speed operation with its magnetic-gearing effect.

Third, the machine performances are summarized in Table I. It indicates that the machine core losses are 43.8W, 35.2W and 23.7W under different magnetizing levels of AlNiCo PM, which are 3.37%, 3.52% and 4.31% of its rated power of 1300W, 1000W and 550W. Thus, it tells that the proposed machine has low power loss and high motor efficiency of 91.5%, 89.9% and 84.6%.

V. Acknowledgments

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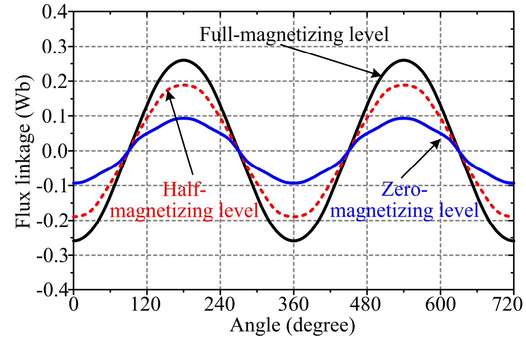

Fig. 3. Flux linkages under different magnetizing levels of AlNiCo PM.

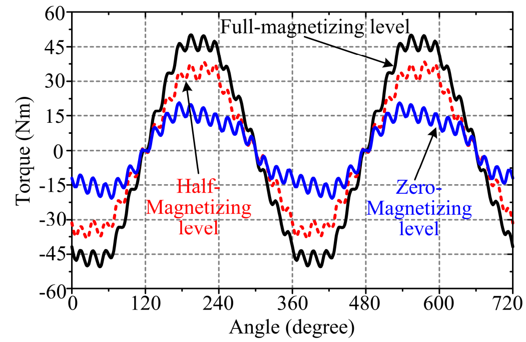

Fig. 4. Torque-angle capabilities under different magnetizing levels of AlNiCo PM.

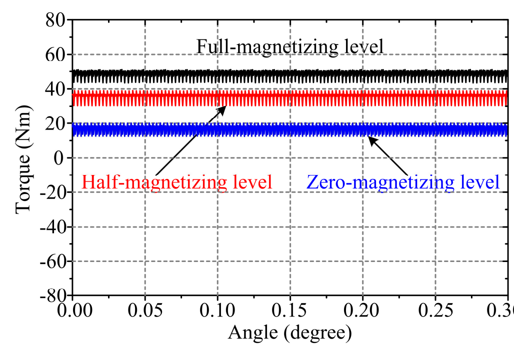

Fig. 5. Steady torques under different magnetizing levels of AlNiCo PM.

TABLE I Machine Performance

Item	**Full-magnetizing level**	**Half-magnetizing level**	**Zero-magnetizing level**
Power	1300 W	1000 W	550 W
Rated torque	48.4 Nm	35.7 Nm	16.5 Nm
Torque ripple	12.4%	22.4%	36.4%
Core loss	43.8 W	35.2 W	23.7 W
Efficiency	91.5%	89.9%	84.6%

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