

A Novel Hybrid-Excited Flux Bidirectional Modulated Machine for Electric Vehicle Propulsion

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Abstract-- This paper presents a novel hybrid-excited flux-bidirectional-modulation (HE-FBM) machine. The key of the proposed machine is to utilize both dc field excitation and permanent magnets (PMs) in the stator/rotor to realize hybrid field excitations and effective flux regulation. In this proposed design, there are two sets of consequent-pole PMs, on the outer stator and on the rotor respectively. Dual magnetic gearing effect is artfully incorporated into the design to ensure an effective magnetic coupling among the magnetic fields excited by the armature windings, the dc field windings and the two sets of PMs. With this arrangement, the air-gap flux can be strengthened or weakened by the adjustment of the dc field current, thereby allowing the electromagnetic torque and output voltage to be effectively regulated over a wide range of speeds. This machine has good application potentials in direct-drive electric vehicle propulsion which needs a wide constant power operation range. The performance of this newly proposed HE-FBM machine is analyzed using finite element method.

Index Terms-- Dual magnetic gearing effect, electric vehicle, finite element method, hybrid-excited, permanent magnet.

I. INTRODUCTION

DIRECT-DRIVE machines have attracted much attention for low-speed high-torque applications, such as electric vehicles (EV) and wind power generators [1, 2]. Due to their inherent high efficiency and high power density features, permanent magnet (PM) machines have been widely used in direct drive applications[3]. Because of the difficulty in controlling their PM flux, traditional PM machines cannot maintain a relatively high efficiency or constant back electromotive force (EMF) over a wide speed range, which restricts their usage in wide-speed-range applications.

Hybrid excited machines have been proposed to realize effective flux control. Both the PMs and the field windings are employed to produce the exciting fluxes[4-9]. In other words, the field flux of these machines can be regulated effectively

with the field winding. An outer-rotor double-saliency PM machine with good flux control is studied for automotive applications in[7]. Because the PMs are only installed in the stator in the machine, its torque density is relatively low when compared to those of its counterparts.

Magnetic gear (MG) has been proposed for many years and become very attractive by virtue of its intrinsic features of high torque density, high efficiency, reduced acoustic noise and low maintenance requirements[10]. MG uses a modulation ring to ensure effective magnetic coupling among the magnetic fields excited by the inner rotor PMs and outer rotor PMs. In[11], a triple-PM-excited MG with improved torque density is proposed. This novel MG can achieve dual magnetic gearing effect since both the outer stator and middle rotor can act as flux modulator. Based on the magnetic-gearing effect, a series of magnetic geared machines have been proposed[12-16]. To simplify the structure, a compact dual-PM-excited machine exploiting magnetic-gearing effect to realize high torque density has been developed, but its air-gap flux cannot be controlled directly[17].

The purpose of this paper is to present a novel hybrid-excited flux-bidirectional-modulation (HE-FBM) machine for electric vehicle propulsion. Compared with traditional flux-modulated machines, this machine enjoys the following advantages:

- i. This machine controls the dc field current directly to regulate the air-gap flux and maintain constant power operation. The flexible field regulation is an important requirement in electric vehicle propulsion.
- ii. This machine has dual magnetic gearing effect, as both the rotor and the outer stator can act as flux modulator. The magnetic fields excited by the outer stator PMs, rotor PMs and armature windings can be modulated and coupled effectively to provide high output torque.
- iii. The pole-pair number of the rotor can be very large and

not constrained by the stator pole-pair number. This makes the machine very suitable for low-speed direct drive applications.

- iv. The reluctance torque is intrinsically high because PMs are inserted into the slots of the ferromagnetic segments in the rotor.

Because of the afore-mentioned merits, this machine has promising application potentials in direct-drive electric vehicle propulsion. The working principle of this proposed machine is discussed. Its performance is analyzed using finite element method (FEM) coupled with external circuit equations.

II. CONFIGURATION AND WORKING PRINCIPLE

A. Configuration of the HE-FBM Machine

Fig. 1 (a) shows the configuration of the proposed HE-FBM machine. It consists of one rotor and two stators. The rotor is located between the inner stator and outer stator. Two sets of consequent-pole PMs are employed, one on the outer stator and the other on the rotor. Both rotor PMs and stator PMs are magnetized in the radially outward direction. Each PM and its adjacent iron tooth/ferromagnetic segment form a pair of magnetic poles. As similar to the modulation ring in the MG, the difference in the permeability between the PMs and steel segments allows both the rotor and outer stator magnetic gearing effect. This dual magnetic gearing effect is the key to ensure effective magnetic coupling among the magnetic fields excited by the armature windings, the dc field windings and the two sets of PMs. The armature windings and dc field windings are housed in the inner stator slots and outer stator slots, respectively. The air-gap flux can be strengthened or weakened directly by the dc field current adjustment.

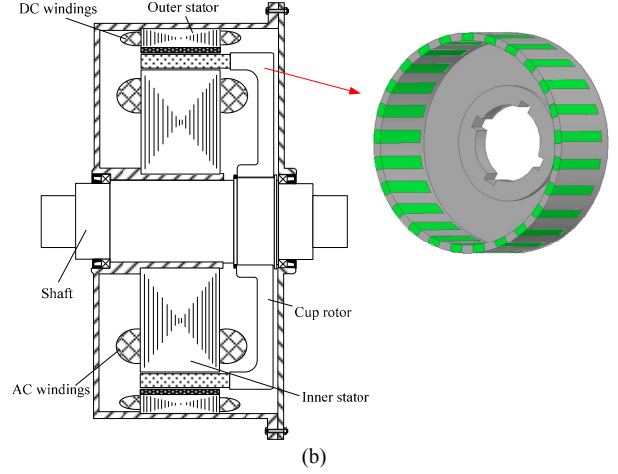
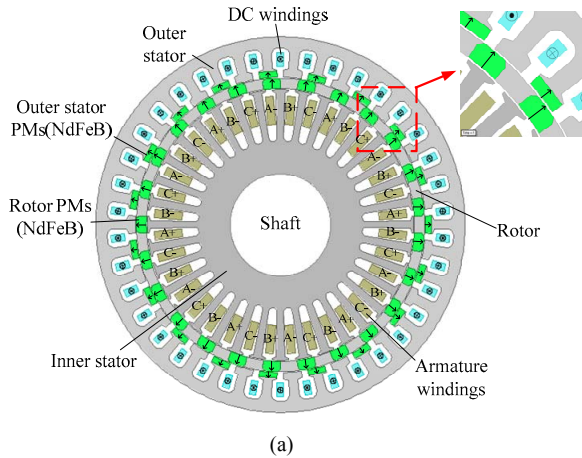


Fig. 1. Configuration and mechanical structure of the proposed HE-FBM machine. (a) Configuration. (b) Mechanical structure.

The mechanical structure of the proposed machine is shown in Fig. 1 (b). The PMs on the outer stator are surface mounted using superglue. Since the rotor is sandwiched between the two stators, a cup rotor structure is artfully used to facilitate the machine assembly. The rotor PMs are glued inside the rotor slots. As there are large centrifugal forces when the rotor rotates at a high speed, a wedge structure is employed at the outer air-gap side to strengthen the rigidity and integrity of the rotor.

B. Working Principle of the HE-FBM Machine

The fundamental operating principle of this HE-FBM machine is based on the magnetic gearing effect, which means that, apart from the fundamental component of the magnetic field, a wealth of field harmonics are produced due to the non-even magnetic field paths as elaborated below. Similar with the working principle of magnetic gears, the space harmonics with the same pole-pair number and same rotational speed are coupled together to produce a steady electromagnetic torque. The space harmonics with different pole-pair numbers or different rotational speeds may produce additional torque ripples.

In order to provide the largest output torque, the best magnetic coupling can be realized when the rotor pole-pairs p_r , outer stator pole-pairs p_s and armature magnetic field pole-pairs p_a are governed by[18]

$$p_r = p_s + p_a \quad (1)$$

To realize flux control, the pole-pair number of the dc windings p_d should be equal to the pole-pair number of the outer stator PMs p_s , namely

$$p_d = p_s \quad (2)$$

and the number of the outer stator slots N_s is governed by

$$N_s = 2p_d \quad (3)$$

In this machine, there are four magnetic sources which are the armature winding, dc winding, rotor PMs and outer stator PMs. Since there are various combinations of the stator and rotor pole-pair numbers for the proposed machine, the preliminary design work involves choosing the most feasible $p_a / p_s / p_r$ combination for better torque performance. To avoid large cogging torque, the least common multiple of any two of these three pole-pair numbers should be as big as possible. While small rotor pole-pairs are more preferable to reduce the armature frequency hence reduce the iron loss. To realize the tradeoff between low iron loss and low cogging torque, the stator is designed with 6 pole-pairs and 36 slots, the outer stator pole-pair number is chosen as 19, and the pole-pair number of the rotor PMs is 25.

III. PERFORMANCE ANALYSIS

The electromagnetic performances of this proposed machine are studied using FEM coupled with external circuit equations. The non-linear behavior of the magnetic material is taken into account, the exact method is given in[19]. Since the rotor is sandwiched between the two stators, the simulation of this proposed machine is however different. Reference [20] gives the method to deal with the simulation when there is a rotating part between two fixed parts. The detailed parameters of the proposed HE-FBM machine are given in Table I.

TABLE I

DESIGN PARAMETERS

Thickness of rotor PMs	3.5mm
Thickness of outer stator PMs	3.5mm
Length of air-gap	0.6mm
Inner stator outside diameter	163.6mm
Outer stator outside diameter	200mm
Stack length	65mm
Number of phases	3
Number of inner stator pole-pairs	6
Number of rotor pole-pairs	25
Number of outer stator pole-pairs	19
Number of inner stator slots	36
Number of outer stator slots	38
Turns of ac conductors	28
Turns of dc conductors	20
Remanence of NdFeB	1.2T
Relative permeability of NdFeB	1.05

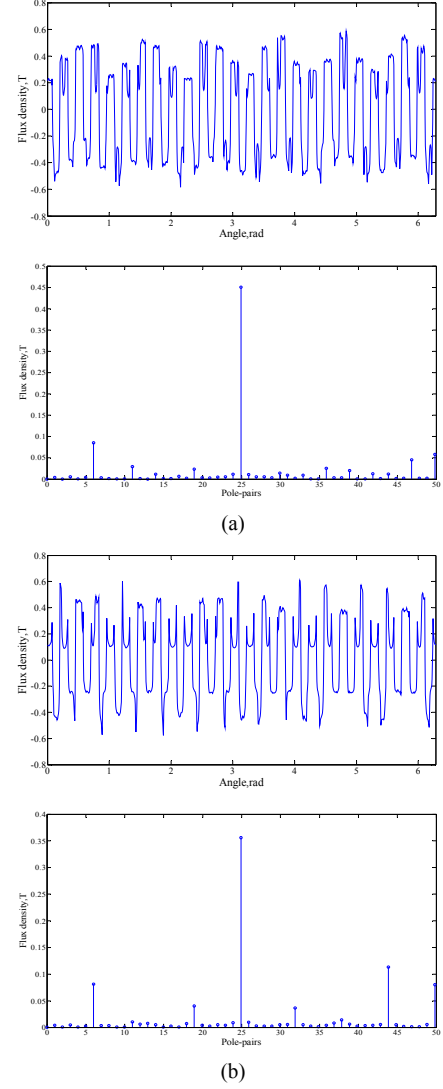


Fig. 2. Flux density waveform and their harmonic spectra when excited only by the rotor PMs. (a) In inner air-gap. (b) In outer air-gap.

Figs. 2-4 show, respectively, the flux density distribution and space harmonics in the air-gap when excited only by the rotor PMs, stator PMs and armature windings. When studying the magnetic field excited only by rotor PMs, the remanence of the PMs on the outer stator is set to zero by changing the material characteristics during the simulation. With this assumption the rotor is shielded from the magnetic fields excited by the outer stator PMs and the permeability of the PMs can be maintained at its original value. The armature current is set to zero, too. The same goes for the results shown in Figs. 3 and 4. When investigating the magnetic field excited only by the outer stator PMs, the remanence of the rotor PMs and armature current are set to zero. When discussing the magnetic field excited by

armature windings, the remanence of both rotor PMs and outer stator PMs is set to zero. From Fig. 2, one can see that the field contains not only the 25 pole-pair harmonic due to the rotor PMs, the 6th and 44th order harmonics are also significant due to the modulating effect of the outer stator. The 6 pole-pair harmonic will react with the 6 pole-pair fundamental component of the armature field to produce a steady torque.

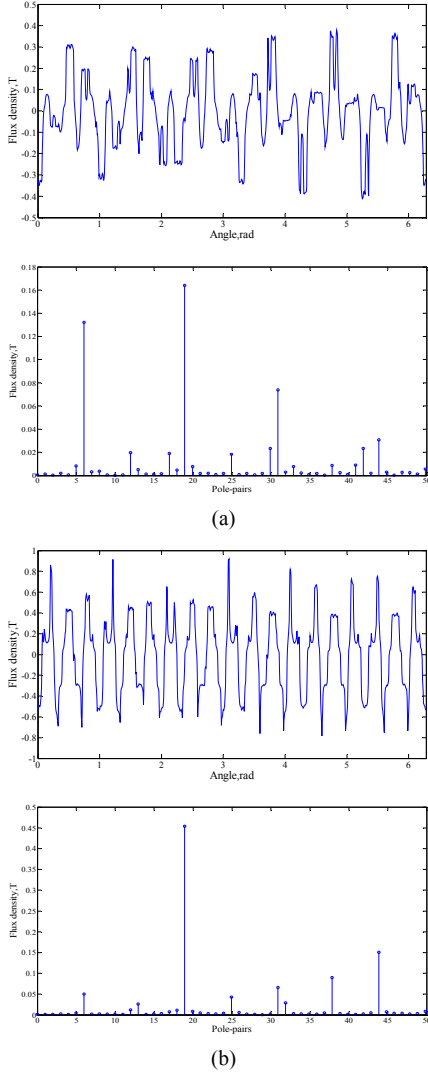


Fig. 3. Flux density waveform and their harmonic spectra when excited only by the outer stator PMs. (a) In inner air-gap. (b) In outer air-gap.

Meanwhile, the field harmonics excited by the outer stator PMs are investigated. Although the stator PMs remain stationary, there will be some rotational harmonics because of the modulating effect of the rotor. As can be seen from Fig. 3, the field excited by the stator PMs will contain harmonics with 19 pole-pairs, 44 pole-pairs and 6 pole-pairs. The stationary 19

pole-pair harmonic will not contribute to torque transmission, but the 6 pole-pair harmonic will interact with the 6 pole-pair fundamental component of the armature field to produce a steady torque. The same phenomenon can be observed in Fig. 4. Besides the 6 pole-pair component of the armature field, space harmonics with 19, 31, 13 and 25 pole-pairs are also apparent because of the modulating effects of both the rotor and outer stator. Harmonic with 25 pole-pairs will couple with the magnetic fields excited by the rotor PMs when transmitting torque. The 19 pole-pair static harmonic will also interact with the magnetic fields excited by the stator PMs and contribute to torque transmission.

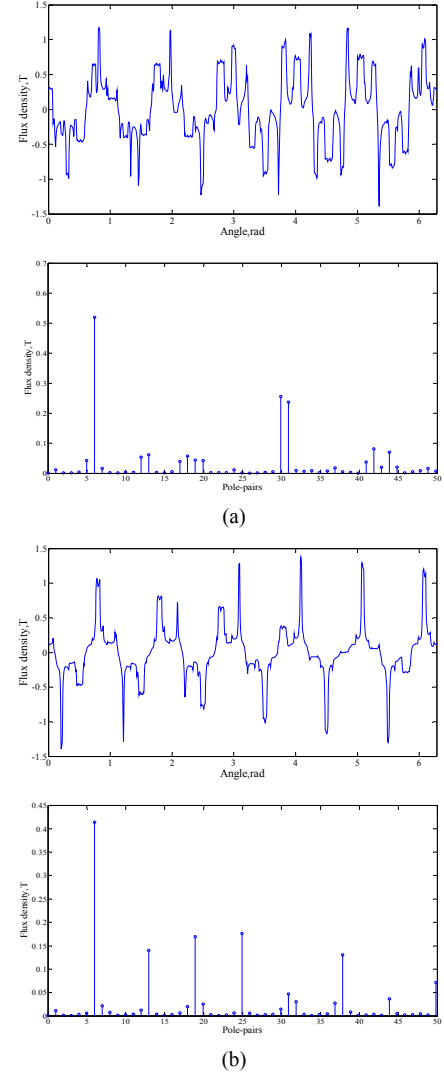


Fig. 4. Flux density waveform and their harmonic spectra when excited only by armature currents. (a) In inner air-gap. (b) In outer air-gap.

The proposed machine employs dc field windings on the

outer stator, and as the air-gap flux can be strengthened or weakened according to different dc field currents, the output torque and induced EMF can be regulated effectively. Compared with ac vector control in a traditional PM machine, the flux control of the proposed HE-FBM machine is much simpler, as only the direction and magnitude of the dc current need to be controlled.

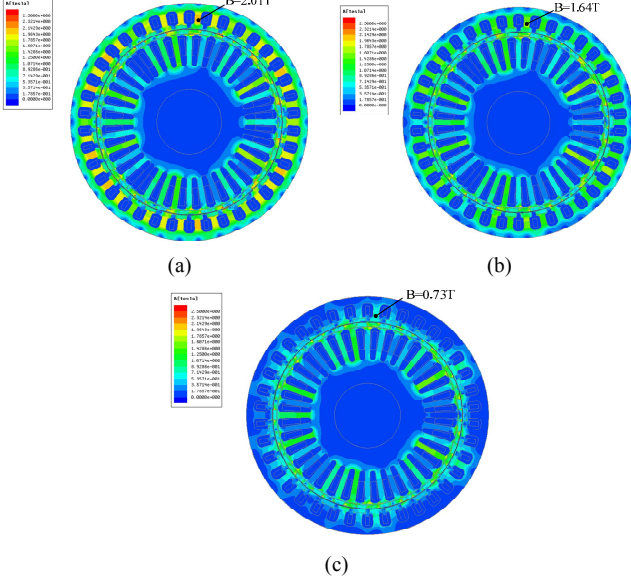


Fig. 5. No-load magnetic field distributions. (a) $F_{dc} = +1000$ A-turns. (b) $F_{dc} = 0$ A-turns. (c) $F_{dc} = -1000$ A-turns.

Figs. 5(a), 5(b) and 5(c) show the no-load magnetic field distributions under operating conditions of flux strengthening ($F_{dc} = +1000$ A-turns), no additional flux control ($F_{dc} = 0$), and flux weakening ($F_{dc} = -1000$ A-turns), respectively. One can see that the magnetic field is regulated effectively. This phenomenon is especially significant in the outer stator. The magnetic field intensity in the outer stator teeth can be regulated from 2.01T to 0.73T. The corresponding air-gap flux density distributions in the outer air-gap are shown in Fig. 6, illustrating that an air-gap flux regulation range of more than 3 times can be realized. Since all the PMs are magnetized in the same direction, the flux density waveforms are not symmetrical. Fig. 7 (a) shows the torque-angle characteristics of this machine with and without flux control under the same armature current. One can see a clear regulation effect on the torque. The maximum torque reaches 107.7 Nm with $F_{dc} = +1000$ A-turns. The maximum torque-time waveforms when the rotor is rotating at rated speed are given in Fig. 7 (b). Cogging torque is also analyzed in this paper, and the results are shown in Fig. 7 (c). It can be seen that the maximum cogging torque is 1.07 Nm, which is only 1% of the maximum transmitted torque.

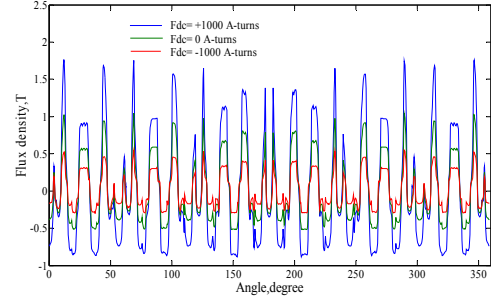


Fig. 6. Flux density distributions in the outer air-gap with different excitations.

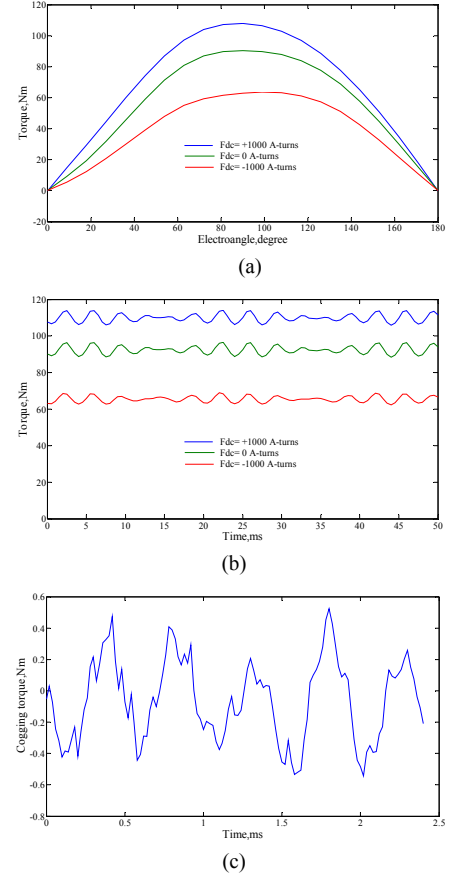


Fig. 7. Torque characteristics of the proposed machine. (a) Torque-angle waveforms. (b) Torque-time waveforms. (c) Cogging torque waveform.

IV. CONCLUSION

This paper proposes a novel hybrid-excited flux bidirectional modulation machine for electric vehicle propulsion. Both the rotor and the stator have PM excitations, the DC field windings are used to achieve bi-directional field regulation. Therefore, the proposed machine can enjoy both high torque density and flexible flux control capability. Compared with machines with all excitation sources in the stator side, the torque density of the

proposed design is improved by 10%. Compared with machines with all excitation sources in the rotor side, this proposed structure eliminates the need to use slip rings and brushes.

Since both PMs and dc windings are employed on the outer stator, the air-gap flux of this proposed machine can be regulated effectively by controlling the dc current. This makes it a suitable candidate for electric vehicle propulsion. The control strategy of the proposed arrangement is much simpler when compared with those of ac controllers, and a regulation range of more than 3 times can be realized.

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