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Novel Hybrid-excited Permanent Magnet Machine Based on the Flux Modulation Effect

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***Abstract*—Hybrid-excited permanent magnet (PM) machines incorporate the merits of both the PM machines and the electric-excited machines, but they usually need slip rings and brushes for the electric excitation and their structures are usually quite complex. In this paper, a novel hybrid-excited PM machine is proposed. Using the flux modulation effect, the PM excitation and the electric excitation are coupled via different field harmonics. It helps the PM to get rid of the risk of irreversible demagnetization. Moreover, the dc excitation coils are accommodated in the stator so that it does not need slip ring or brush, making the machine simple and reliable. The working principle and electromagnetic performance of the machine are validated using finite element method (FEM).**

Keywords—flux modulation, hybrid excitation, permanent magnet.

I. INTRODUCTION

Permanent magnet (PM) machines are becoming more and more popular in various applications due to their merits of high power density and high efficiency [1-3]. However, in conventional PM machines, the airgap flux is hard to adjust, which limits their utilization in some wide-speed-range applications, such as electric vehicles, electric boats, and wind power generation. Hybrid-excited machines (HEMs) use both PM and electricity for the magnetic field excitation. As a result, they inherit the merits of PM machines and in the meanwhile, their airgap field can be adjusted by changing the electric excitation.

In literature, many different hybrid-excited PM machines have been proposed [4-8]. According to the relationship between the flux paths of the PM and the electric excitation, the hybrid-excited PM machines can be classified into three categories, namely the series flux-path type, the parallel flux-path type, and the paratactic flux-path type. The series flux-path HEMs can have simple structures and high torque densities. However, due to the high flux reluctance, the electric excitation is less effective and the PM may be irreversibly demagnetized during flux weakening operation. The parallel flux-path HEMs are more efficient for electric excitation and they also have no risk of irreversibly PM demagnetization. However, their torque densities are usually lower. The paratactic flux-path HEMs usually have two different flux-paths and their structures are hence more complex.

A common problem for these HEMs is that, the dc coils in the rotor need to be excited via slip rings and brushes, which lowers the machine reliability and increases the maintenance. In some recent researches, it is proposed to place the excitation coils and the PMs in the stator, which is mostly realized by a doubly salient structure. However, the doubly salient structure causes big cogging torque and lowers the power density [9-10].

In this paper, a novel hybrid-excited PM machine based on the flux modulation effect is proposed. Unlike previous designs, the PM excitation and the electric excitation are coupled via field harmonics in this machine. The PMs hence have no risk of irreversible demagnetization. The machine does not need slip rings or brushes since the dc excitation coils are placed in the stator, which makes the structure simple and reliable. In this paper, the structure and the working principle of the proposed HEM are introduced first. Its electromagnetic performance is analyzed using time-stepping finite element method (FEM).

II. CONFIGURATION AND WORKING PRINCIPLE

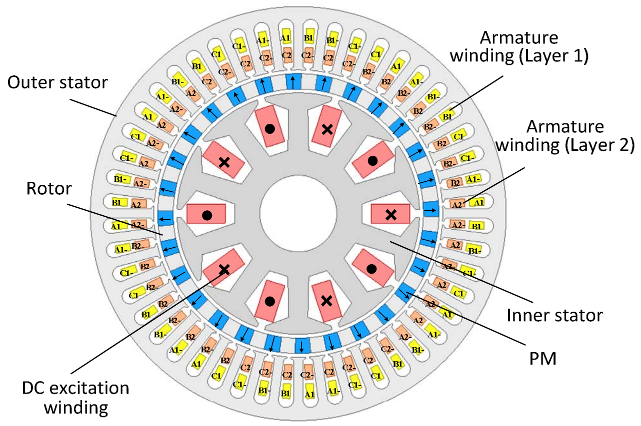

Fig. 1. Configuration of the proposed machine.

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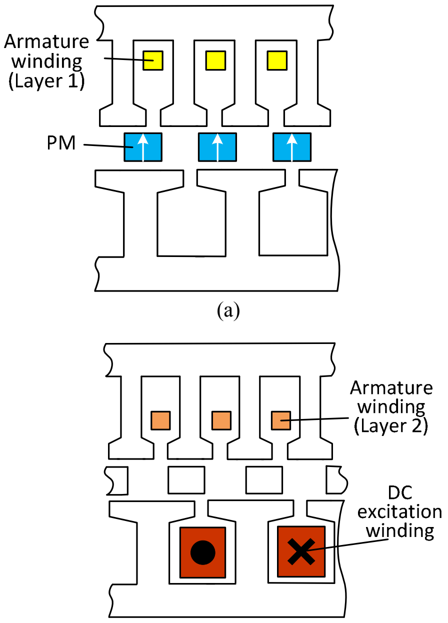
A. *Machine structure*

Fig. 1 shows the configuration of the proposed HEM. It has an outer stator, an inner stator and a rotor in between. The rotor consists of PMs and ferrite poles which are arranged alternatively. The armature winding is housed in the outer stator and the dc excitation winding is housed in the inner stator. Unlike conventional double-layer windings, in this machine, the two layers of armature winding are coiled with different pole-pair numbers, so that layer 1 of the armature winding interacts with the PM-excited field, while layer 2 of the armature winding interacts with the electric-excited field through the flux modulation effect as shown in Fig. 2. The two layers of armature winding are connected in series and the total induced voltage is decided by both the PM excitation and the electric excitation. By adjusting the excitation current, the total induced voltage can be controlled, which is equal to the flux weakening or strengthening in conventional machines.



(a)

(b)

Fig. 2. Interactions between (a) armature winding layer 1 and the PM excitation and (b) armature winding layer 2 and the electric excitation.

B. *Flux Modulation and Hybrid Excitation*

The interaction between layer 1 of the armature winding and the PM is like a conventional PM synchronous machine. The interaction between layer 2 of the armature winding and the dc excitation is by the flux modulation effect which is briefly explained as follows.

When a dc current is applied to the excitation coils, the field is produced by both the PM and the excitation current. If we only consider the fundamental component, the produced magnetomotive force (MMF) can be expressed as,

$$F \approx F_{PM}\cos[N_{PM}(\theta-\omega t)+\phi_1]+F_{DC}\cos(P_{DC}\theta+\phi_2) \quad (1)$$

where; the subscript "*PM*" refers to the permanent magnets; the subscript "*DC*" refers to the dc excitation; θ and ω are the mechanical position and speed of the rotor, respectively; ϕ_1 and ϕ_2 are the initial phase angles.

As the PMs and the ferrite poles have different permeability, the airgap is magnetically uneven. If the slot opening is ignored, the airgap permeance can be expressed as,

$$P \approx P_0 + P_1\cos[N_{PM}(\theta-\omega t)+\phi_3] \quad (2)$$

Since the PMs and ferrite poles are arranged alternately, F_{DC} and P_1 are opposite in phase angles, namely $\phi_3 = \phi_1 + \pi$.

The flux density B in the airgap is the product of F and P.

$$B \approx \left\{\begin{array}{l} P_0F_{PM}\cos[N_{PM}(\theta-\omega t)+\phi_1]+P_0F_{DC}\cos(P_{DC}\theta+\phi_2) \\ -\frac{1}{2}P_1F_{PM}\cos[2N_{PM}(\theta-\omega t)+2\phi_1] \\ -\frac{1}{2}P_1F_{DC}\left\{\begin{array}{l}\cos[(N_{PM}+P_{DC})(\theta-\frac{N_{PM}\omega}{N_{PM}+P_{DC}}t)+\phi_1+\phi_2] \\ +\cos[(N_{PM}-P_{DC})(\theta-\frac{N_{PM}\omega}{N_{PM}-P_{DC}}t)+\phi_1-\phi_2]\end{array}\right\} \\ -\frac{1}{2}P_1F_{PM} \end{array}\right\} \quad (3)$$

In the proposed HEM, the pole-pair numbers of winding layer 1 and layer 2 are designed to be N_{PM} and N_{PM} - P_{DC}, respectively. Due to the existence of the N_{PM} component, voltage will be induced in layer 1 of the armature winding and its frequency is,

$$f_1 = \frac{N_{PM}\omega}{2\pi} \quad (4)$$

Similarly, the frequency of the voltage induced in winding layer 2 is,

$$f_2 = \frac{N_{PM}\omega}{N_{PM}-N_{DC}}\cdot\frac{N_{PM}-N_{DC}}{2\pi} = \frac{N_{PM}\omega}{2\pi} \quad (5)$$

Clearly, the induced voltages in winding layer 1 and lay 2 have the same frequency. Ideally, both of them are sinusoidal. As a result, the two layers of armature winding can be connected in series. When the machine needs to operate at a high speed, the induced voltage can be controlled within the limits of the connected power converter by changing the dc excitation current, which realizes the same target of flux weakening in other HEMs.

Compared with previous HEMs, the salient features of the proposed design can be concluded as follows.

- Both the PMs and the dc coils are arranged in the stator, so that it does not need slip ring or brush for the electric excitation. The machine reliability is improved and the maintenance is reduced.
- As the effective PM field and electric-excited field have different pole-pair numbers, the PMs have little risk of being irreversibly demagnetized by the electric excitation.
- Compared with the HEMs with doubly salient structure, the cogging torque of this machine is smaller.

III. DESIGN CONSIDERATIONS

For the induced voltages in the two winding layers to be effectively superposed, their phase angles need to be same. From (3), it can be seen that the phase angle of the induced voltage in winding layer 1 is decided by the rotor position ϕ_1; while the phase angle of the induced voltage in winding layer 2 is decided by both the rotor position ϕ_1 and the inner stator position ϕ_3. Hence, if we change ϕ_3, only the phase angle of the induced voltage in winding layer 2 will be affected, and the phase angle difference in two winding layers can be adjusted. The appropriate inner stator position can be investigated using FEM.

The slot space distribution for the two winding layers should be designed according to the expected speed range or the field weakening ability. If layer 1 winding takes for space, the machine will have better torque and efficiency performance at lower speed operation. If layer 2 winding takes more space, the machine will have a better voltage regulation ability and wider speed range. As this paper is mainly about the working principle validation, only a preliminary design is analyzed. In this design, each winding layer takes half of the slot space. The principle parameters of this design is listed in Table I.

TABLE I
PRINCIPLE DATA OF THE PROPOSED DESIGN

Quantity	Value
Outer radius	108.0 mm
Inner radius of outer stator	75 mm
Outer airgap length	0.8 mm
Inner airgap length	0.8 mm
Radial thickness of PMs	8.0 mm
Number of the rotor PMs	28
Pole-pair number of the dc winding	5
Number of stator slots	48
Pole-pair number of winding layer 1	28
Pole-pair number of winding layer 2	23
Stack length	65 mm
Steel type	M19_24G
PM remanence	1.2 T

IV. PERFORMANCE ANALYSIS

To validate the concept of hybrid excitation by flux modulation, the proposed design is analyzed using FEM. The flux distribution of the machine is first investigated. When the machine is excited by only the PMs, the flux distribution is plotted in Fig. 3. The waveform of the radial component of the airgap flux density is shown in Fig. 4. Clearly, the airgap flux mainly has a 28 pole-pair component. It can also be found out through the corresponding harmonic analysis as depicted in Fig. 5.

When a dc current is applied to the excitation coils, the airgap flux density and the corresponding harmonic analysis are shown in Figs. 6 and 7, respectively. It can be seen that, when the electric excitation is added, some other harmonic components, especially the 5-pole-pair and the 23-pole-pair ones, also become significant. This corresponds well with the theoretical analysis results in Section II(B). It can be expected that, when there is only the PM excitation, voltage will be induced in only winding layer 1. When there are both PM and electric excitations, voltage will be induced in both winding layers.

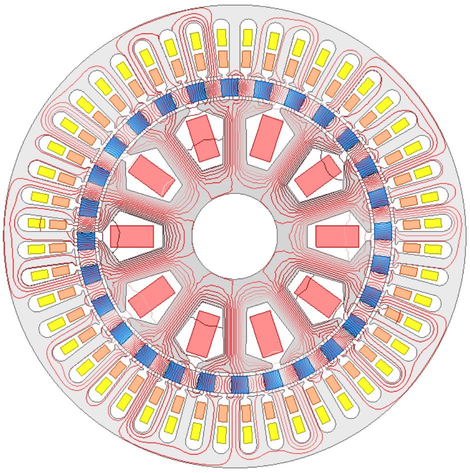


Fig. 3. PM flux distribution.

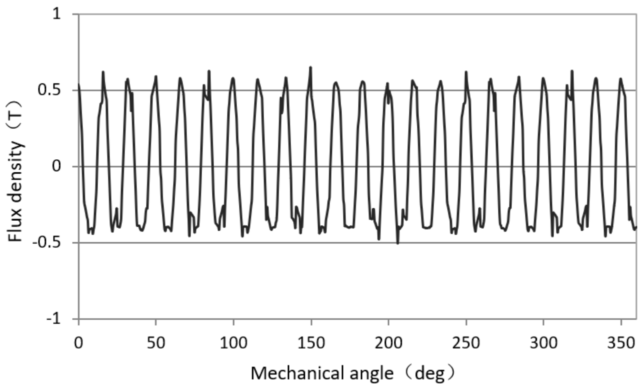


Fig. 4. Airgap flux density due to the PM excitation.

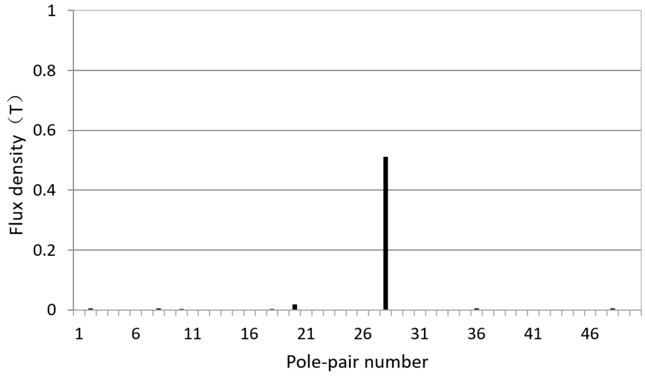


Fig. 5. Harmonic analysis of the airgap flux density due to the PM excitation.

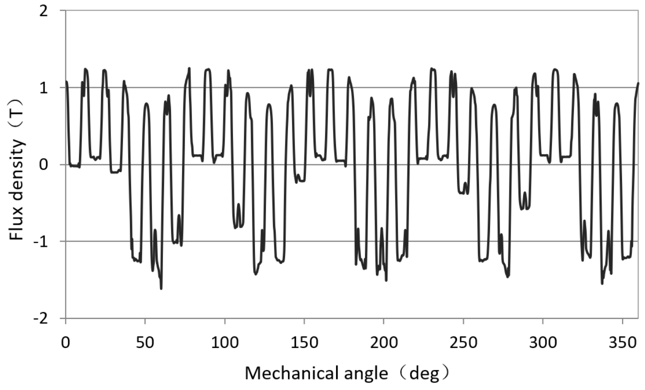


Fig. 6. Airgap flux density due to hybrid excitation.

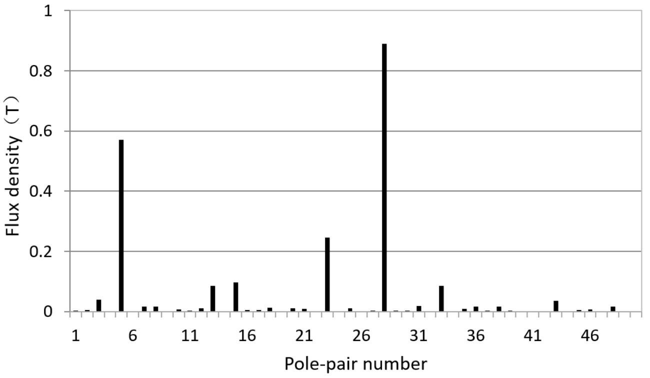


Fig. 7. Harmonic analysis of the airgap flux density due to hybrid excitation.

When a 1500 Ampere-turn excitation, which is equal to a 4 A/mm^2 current density excitation, is applied to the dc coil, the induced voltage in the armature winding is shown in Fig. 8. Clearly, due to the induced voltage in winding layer 2, the total induced voltage is raised up by the dc excitation. When a -1500 Ampere-turn dc excitation is applied, the induced voltage is effectively reduced as shown in Fig. 9. It can be seen that the induced voltages in two winding layers are not ideally sinusoidal since there are harmonics in the airgap field. It is worth further investigation to get more similar voltage waveforms in two winding layers.

When the machine is operating at 300 rpm, the electromagnetic torque and the cogging torque are shown in Fig. 10. As is expected, the torque ripple is smaller than that of most doubly salient PM machines and it is acceptable for common traction applications.

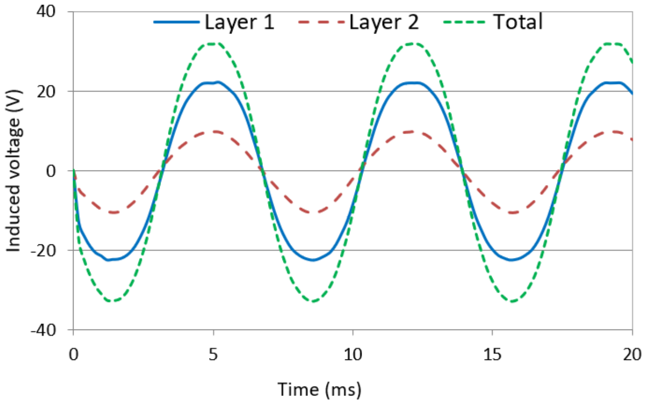


Fig. 8. Back-EMF when the dc excitation is 1500 Ampere-turn.

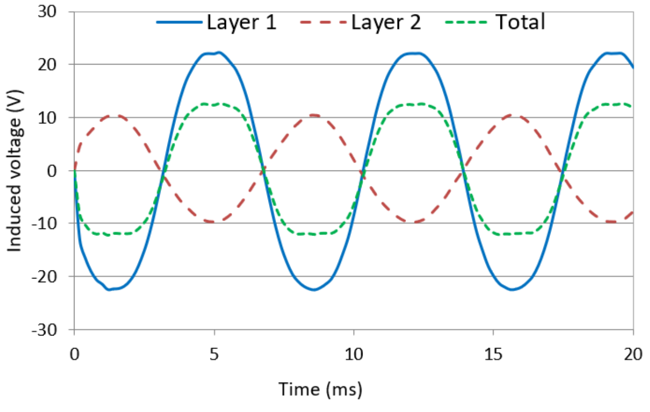


Fig. 9. Back-EMF when the dc excitation is -1500 Ampere-turn.

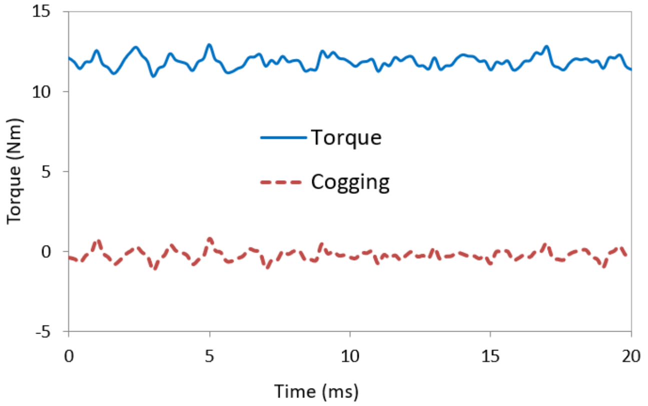


Fig. 10. Back-EMF when the dc excitation is -1500 Ampere-turn.

V. CONCLUSION

In this paper, a novel hybrid-excited PM machine based on the flux modulation effect is proposed. Its back-EMF can effectively controlled by adjusting the dc excitation. Compared with previous HEMs, it has both the armature and excitation windings in the stator, and it does not need slip ring or brush. The torque ripple is also smaller than that of the doubly salient PM machines. The working principle and the performance of a preliminary design are validated using FEM.

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