A new Magnetic Field Modulation Type of Brushless Double-Fed machine

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Background

Direct drive systems based on permanent magnet (PM) machines are one of the main methods to improve operation efficiency and simplify system structure, in which PM machines are required to possess the performances of low speed and high torque output. Thus, the design with a large numbers of stator slot and rotor pole are always adopted in the direct drive PM machines, resulting in a bulky machine volume. Therefore, a new type of magnetic field modulation (MFM) PM (MFM-PM) machines have been proposed and investigated widely. Based on the field modulation effect, MFM-PM machines can provide high torque with low speed operation, so as to be suitable for low speed direct drive applications, such as renewable power generation and electrical propulsion. However, similar with conventional PM synchronous machine, the operation range of MFM-PM machine is restricted since the uncontrollable PM excitation field. So, hybrid excitation (HE) design concept has been introduced into MFM-PM machine to achieve the flexible flux controllability.

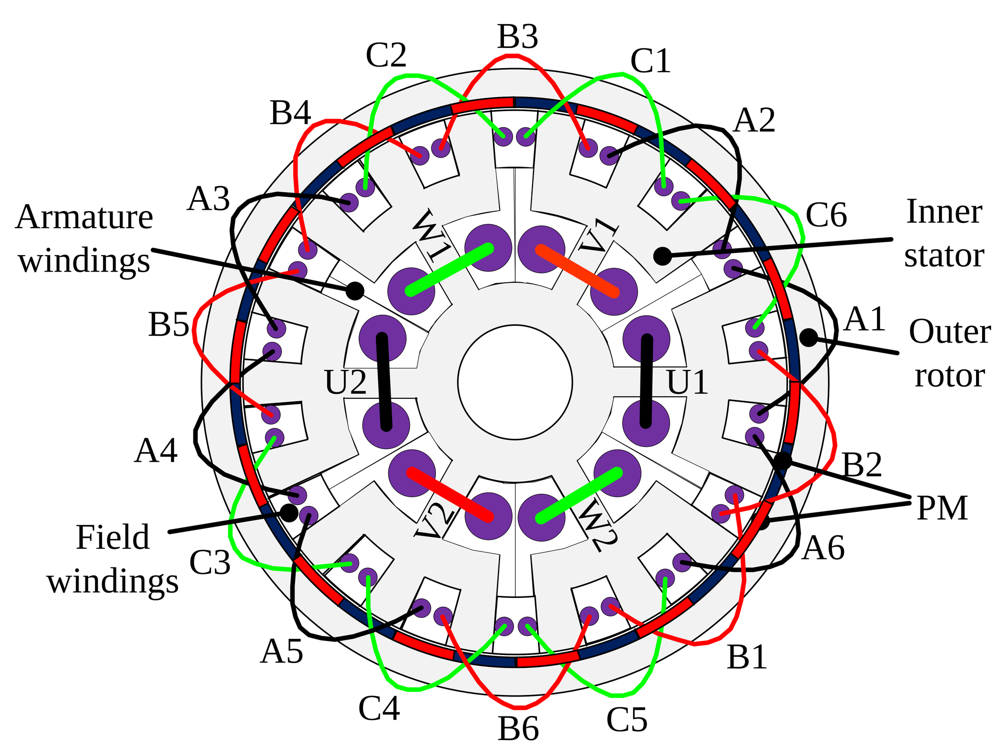
In this paper, a new MFM type of brushless double-fed (MFM-BDF) machine is proposed, in which the outer rotor and inner stator arrangement is adopted. The split-pole structure is employed in the inner stator to obtain the modulating poles on each stator tooth, so that the MFM effect can be achieved to increase its torque density. The field windings are embedded in the dummy slots between each adjacent modulating poles. Thus, the proposed MFM-BDF machine can artfully integrates two merits of offering the low speed with high torque output and providing the high speed using flux weakening control.

Conclusion

By artfully integrating the double-fed concept and MFM machine, a new MFM-BDF machine is proposed in this paper. The field windings are embedded between the modulating poles, so that the machine space can be fully utilized. The machine configuration and operation principle are discussed. Based on the FEA, the static characteristics such as the flux linkage, torque and cogging force are analyzed. It confirms that the proposed machine possesses a high torque density due to the MFM effect. By feeding flux enhancing field current and flux weakening field current, the operation region and the cogging torque can be enlarged and reduced.

Topology and Operation Principle

Topology



Configuration of proposed MFM-BDF machine.

The proposed MFM-BDF machine, in which the outer-rotor and inner stator arrangement is adopted. The structure of outer rotor with 14 pole-pair number PMs surface-mounted is similar with those of conventional PM machines, so it possesses the merits of ease of manufacture, robustness and reliability. Besides, a split-pole structure is employed in the inner stator, namely the inner stator equips 6 stator teeth to house 4 pole-pair number armature windings and each stator tooth has three modulating poles. These modulating poles function to modulate the air-gap magnetic field and accommodate 14 pole-pair number AC field windings, so that the spaces between the adjacent modulating poles are fully utilized, thus improving the torque density and magnetic field regulation capability.

Operation Principle

The proposed MFM-BDF machine operates based on magnetic field modulation effect. G_r named magnetic gear ratio is the rotation speed ratio between the armature reaction magnetic field and the rotor, which is governed by

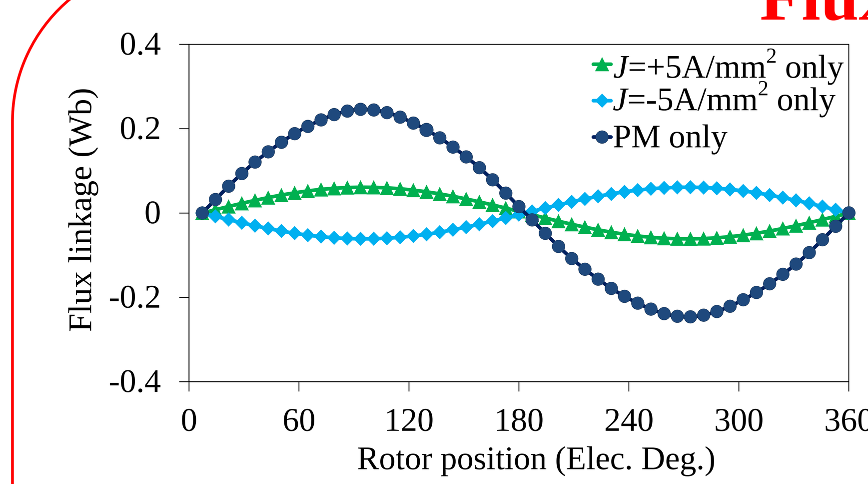
$$\omega_s = \frac{p_r}{p_s}\omega_r = G_r\omega_r$$

where p_r and p_s are the pole-pair numbers of rotor PMs and armature windings, respectively.

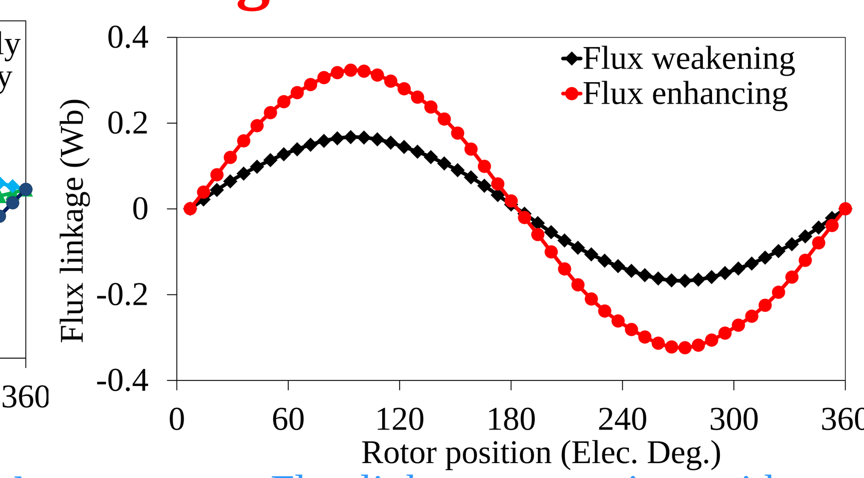
A rotational MMF will be produced when the AC current is fed into field windings, which exhibits the identical pole-pair numbers with that of equivalent MMF excited by PMs. Simultaneously, the air gap magnetic field will be enhanced or weakened by adjusting the phase of field current.

Performance Analysis

Flux linkage



Flux linkage waveforms due to PMs only, J=-5A/mm² only and J=+5A/mm² only.



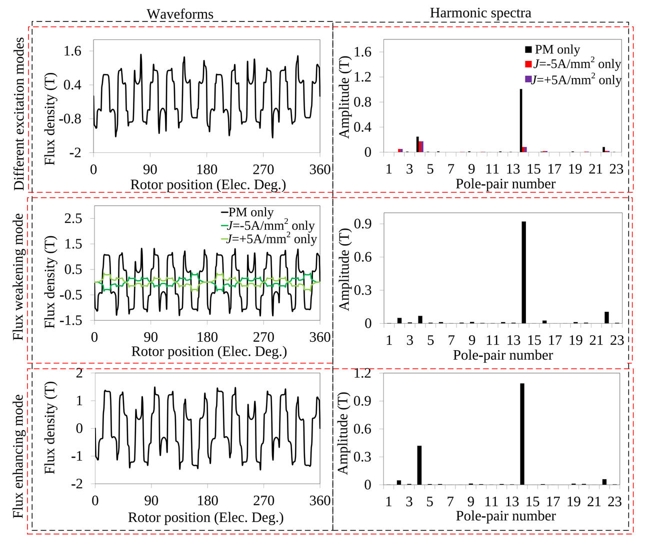
Flux linkage comparison with different excitations.

The phases of flux linkage waveforms caused by flux weakening field current and flux enhancing field current are opposite and identical with that of flux linkage waveforms due to PMs only, so the expected flux weakening and flux enhancing operations can be realized by injecting corresponding currents into field windings, which is consistent with the flux linkage with different excitations.

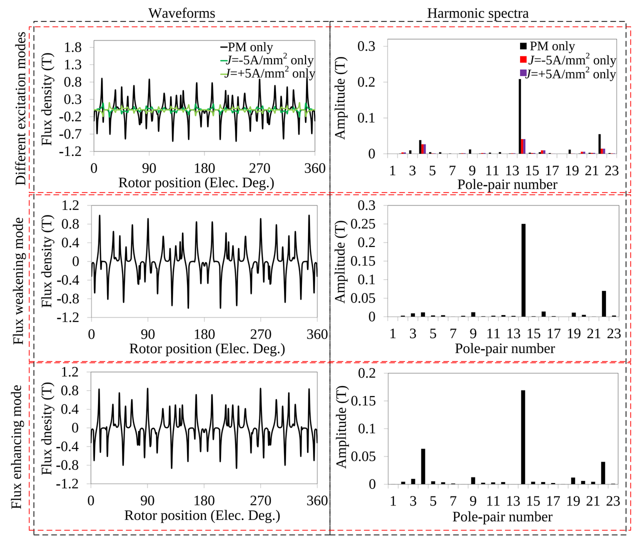
Performance Analysis

Air-gap flux density and harmonic spectrums

There are a number of asynchronous space harmonics due to the MFM effect of modulating poles in despite of different excitation and the main harmonics including the 4th and 14th ones. The 4th and 14th harmonic component amplitudes of radial flux density in flux weakening and flux enhancing operations are reduced and improved obviously, respectively, which indicates the reduction and improvement of 3-phase flux linkages linked by armature windings with 4 pole-pair, respectively. However, the 14th harmonic component amplitudes of tangential flux density is increased and reduced in flux weakening and flux enhancing operations on the contrary.

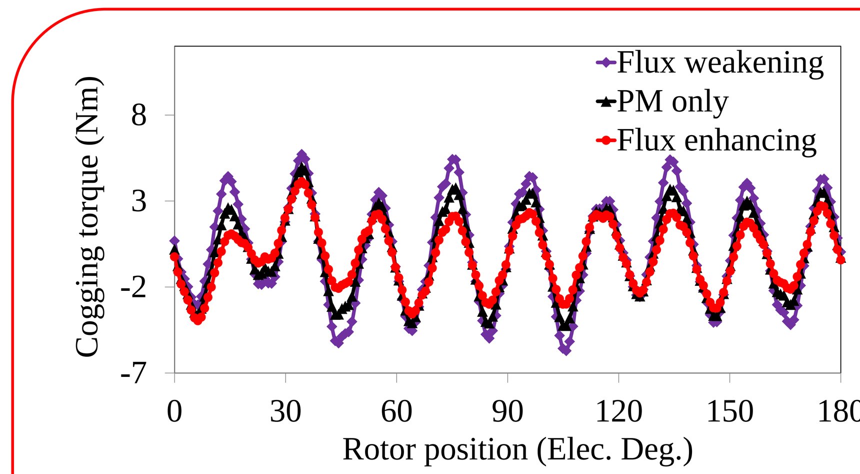


Radial component.



Tangential component.

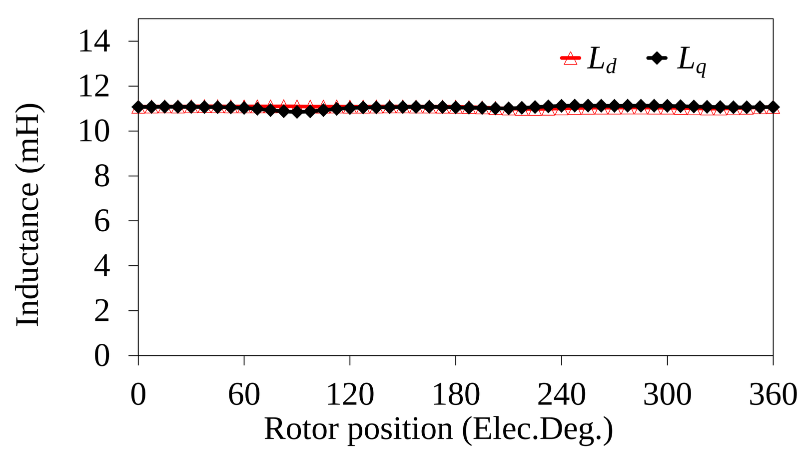
Cogging Torque and Inductance



Cogging torque with different field excitations.

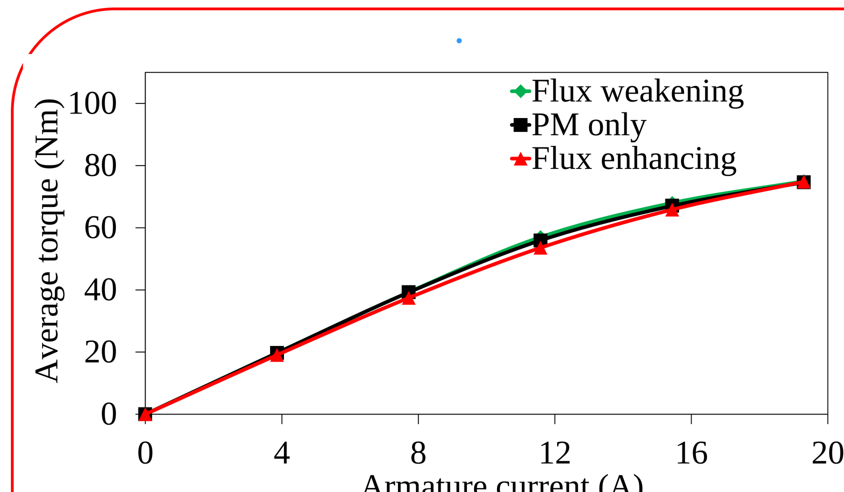
The cogging torque peak-to-peak value of proposed machine in flux weakening operation is higher than that with PM excitation only, and that in flux enhancing operation is the lowest one.

Due to $L_d = L_q$, the i_d =0 control method is adopted to obtain the highest torque current ratio.



Inductance waveforms.

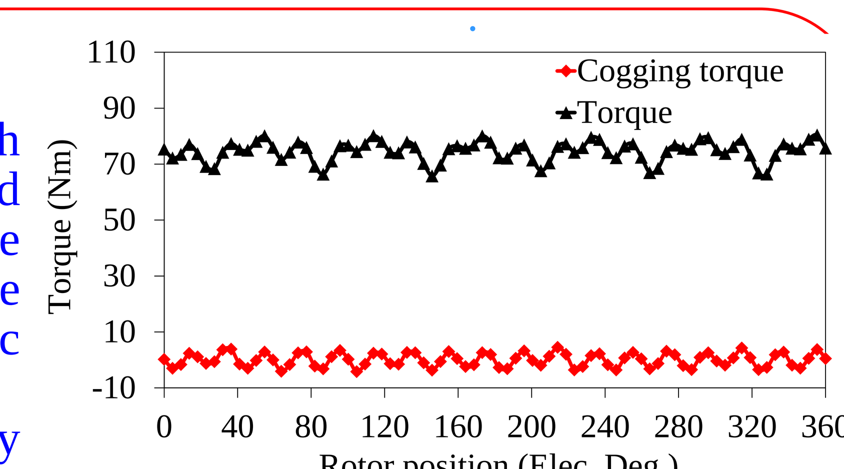
Torque



Torque waveforms with different excitations.

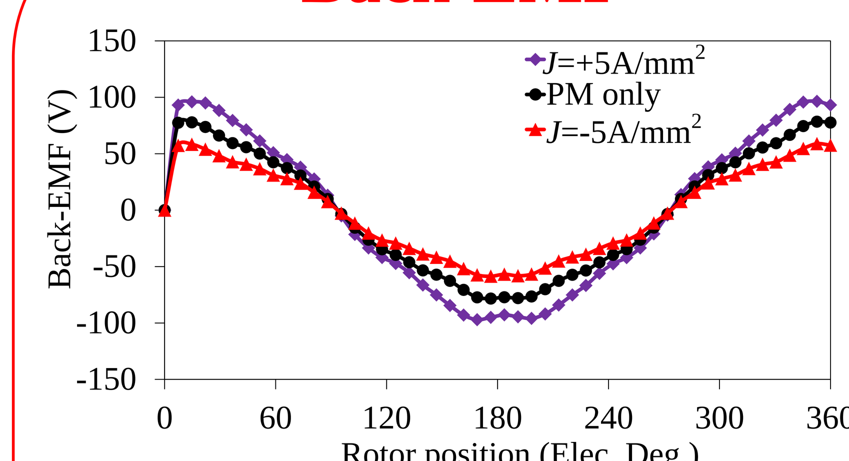
The average torque increases linearly with the armature current when it is below the rated value of 12A, whereas the increase of average torque is gradually clipped when beyond the rated armature current due to the magnetic saturation occurs at the iron core.

The waveforms of output torque excited by PM only and cogging torque are drawn for comparison. It can be obtained that the torque ripple is mainly affected by the cogging torque.



Comparison of output torque and cogging torque

Back-EMF



No-load EMF waveforms with different excitations.

The no-load EMF can be regulated by injecting different field currents. So, the operation region of proposed can be enlarged by adopting flux weakening field current under the limited DC bus voltage.