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Comparative study of biased flux permanent magnet machines with doubly salient permanent magnet machines considering with influence of flux focusing

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ABSTRACT

Different from the doubly salient permanent magnet (PM) machines (DSPMMs), the stator/rotor pole number combination (N_s/N_r) in biased flux PM machines (BFPMMs) is flexible and N_r can be any integer except the phase number and its multiples. When N_s/N_r differ by one, 6-stator pole BFPMM exhibits bipolar phase flux-linkage and symmetrical phase back-electromotive force waveforms. Based on the optimal 6/7 N_s/N_r and the rated copper loss, the torque density of BFPMMs is enhanced by 19%, 18.8% and 40.3% respectively when employing the flux-focusing structures with inner-type, outer-type and combined-type. Meanwhile, the PM utilization efficiency is also enhanced. Moreover, based on the inner-type flux-focusing structure, the optimized 6/7 N_s/N_r BFPMM exhibits about 18% higher average torque and 80% lower torque ripple than the optimized 6/4 N_s/N_r DSPMM. Further, the unbalance between phases which is observed in DSPMMs is overcome in the BFPMMs. The analyses are validated experimentally on a prototype machine.

1. Introduction

Switched reluctance machine (SRM) has been investigated extensively over the last decades due to its low cost, simple and robust structure [1–5]. However, the torque density of SRM is relatively lower compared with permanent magnet (PM) machines. To enhance the torque density, PMs can be added into the stator of basic SRMs. Doubly salient PM machine (DSPMM) [6–15] is one of the proposed machine topologies, in which PMs are located in the stator back iron with the span number of stator pole equal to the phase number and concentrated windings are employed. However, it has unipolar flux linkage, relatively low torque density and high torque ripple.

Refs. [7,8] analyse the principle of the electromagnetic torque generation and the influence of different geometry parameters of DSPMM in detail. The phase back-EMF waveform of DSPMM is trapezoidal [7–9], which is suitable for brushless DC (BLDC) operation [10]. On the other hand, the rotor-skewing method [11] can be used to make back-EMF waveform more sinusoidal. Consequently, DSPMM can also operate in the brushless AC (BLAC) mode [11,12]. Nevertheless, due to the asymmetric flux path in the stator of DSPMM, the flux-linkage and back-EMF of each phase are unbalanced, particularly under heavy magnetic saturation.

In this paper, the biased flux PM machine (BFPMM) with doubly salient structure and alternate polarities of PMs circumferentially located in the stator back iron between adjacent stator poles is investigated, which can eliminate the asymmetric flux path in the stator of DSPMM. Firstly, the operation principle and stator/rotor pole combinations are illustrated. Then, three types of flux focusing structures are proposed to enhance the torque performance. Based on the inner type flux focusing structure, the electromagnetic performance of BFPMM is compared with DSPMM. Finally, a prototype of BFPMM (6/7 stator/rotor poles, inner type flux focusing structure) is manufactured and measured to validate the analyses.

2. Machine operation principle and stator/rotor pole combinations

2.1. Topologies and operation principle

The stator of biased flux permanent magnet (PM) machine (BFPMM) consists of T-shape laminated segments between which

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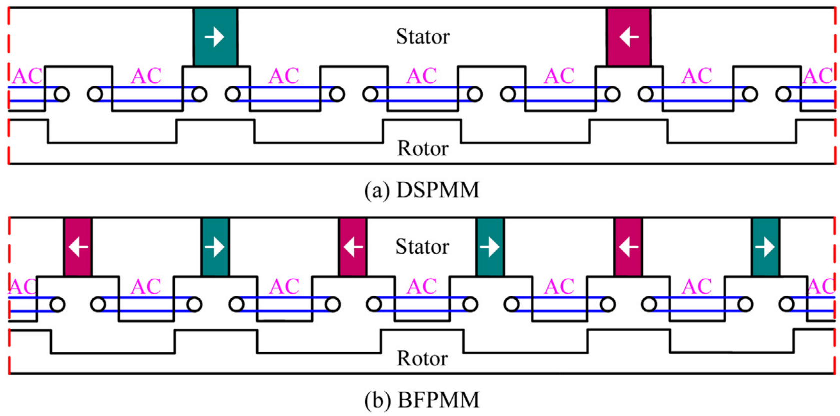

Fig. 1. Structure evolution from DSPMM to BFPMM in 6/4 stator/rotor pole combination.

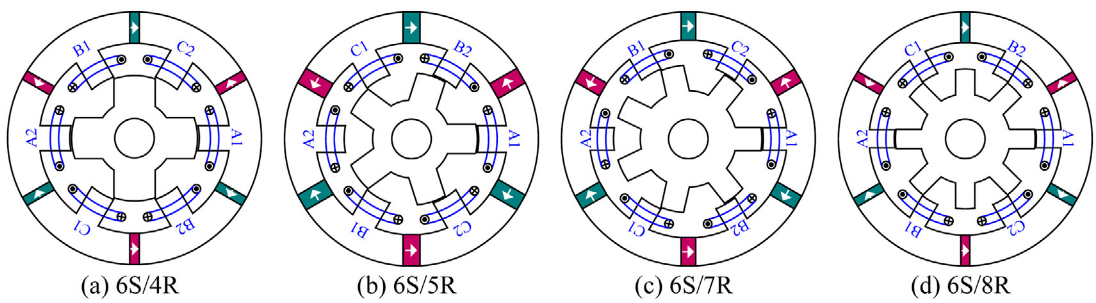

Fig. 2. Topologies of 6-stator pole BFPMMs with different rotor pole numbers.

circumferentially magnetized PMs of alternate polarities are placed, and non-overlapping windings are wound around each stator pole. The rotor of BFPMM has salient structure, as shown in Figs. 1 and 2. Meanwhile, the span number of stator poles between the alternate polarity PMs in the stator back iron is the main difference between BFPMM and doubly salient PM machine (DSPMM). For BFPMM, this number is equal to one while that of DSPMM is equal to its phase number.

2.2. Stator and rotor pole combinations

Different from DSPMM in which the stator and rotor pole (N_s/N_r) combinations are restricted to Eqs. (1) and (2) [13], the N_s/N_r combinations in BFPMM are more flexible. The rotor pole number can be any integer except the phase number and its multiples. Hence, the choices of N_s and N_r of BFPMM can be summarized by Eqs. (1) and (3).

$$N_s = 2mk \tag{1}$$

$$N_r = N_s \pm 2k \tag{2}$$

$$N_r = N_s \pm j (N_r \neq k_i m, j = 1, 2 \ldots, k_i = 1, 2 \ldots) \tag{3}$$

where m is the phase number, k, j and k_i are integers.

The conventional coil-EMF phasor method can be used in BFPMM to determine the coil connections of the armature windings [16]. According to Eq. (4), the electric angle α_e between two adjacent coil-EMF phasors can be derived from the mechanical angle α_m and the rotor pole number N_r.

$$\alpha_e = N_r \alpha_m \tag{4}$$

Fig. 2 shows the topologies of 6-stator pole BFPMMs with the main rotor pole numbers (optimal winding factors). Based on Eq. (4) and further considering the opposite polarities of adjacent coils caused by the PMs in the stator back-iron, the coils of the same phase are connected in series with the same polarity (opposite polarity together with 180 electric degree shifting) in 5- and 7-rotor pole BFPMMs but with the opposite polarity in 4- and 8-rotor pole BFPMMs, as shown in Fig. 2. These four BFPMMs are all globally optimized with the objective of maximum average torque under the rated 30W copper loss by genetic algorithm (ANSYS Maxwell). The phase flux-linkage waveforms of four N_s/N_r combinations are compared in Fig. 3. It can be seen that 5- and 7-rotor pole BFPMMs have bipolar phase flux-linkages whilst 4- and 8-rotor pole BFPMMs exhibit unipolar phase flux-linkages. As shown in Fig. 4, since the even harmonics in a single coil which cause the asymmetric back-EMF are eliminated in the phase winding, 5- and 7-pole BFPMMs exhibit symmetrical phase back-EMF waveforms. Further, due to the influence of electric frequency, the 7-rotor pole BFPMM exhibits higher magnitude of phase back-EMF than the 5-rotor pole BFPMM under the same speed. Fig. 5 compares the average torque of four

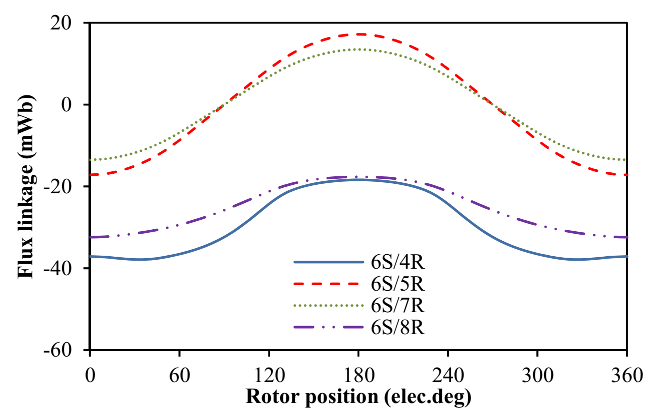

Fig. 3. Open-circuit phase flux-linkage of 6-stator pole BFPMMs with different rotor pole numbers.