Influence of Inner/Outer Stator Pole Ratio and Relative Position on Electromagnetic Performance of Partitioned Stator Switched Flux Permanent Magnet Machines

J. T. Shi, and Z. Q. Zhu, Fellow, IEEE

Abstract—Based on the 6-pole outer stator (armature winding-stator), the influence of inner (permanent magnet-stator)/outer stator pole ratio \( n \) \((n=N_{\text{IS}}/N_{\text{OS}})\), stator relative positions and rotor pole number combinations on electromagnetic performance of partitioned stator switched flux permanent magnet (PM) machines (PS-SFPMMs) is investigated in this paper. Since the armature windings and PMs are located in two separated stators and PMs are stationary, PS-SFPMMs have high fault tolerance capabilities. To maximize the torque performance, the PM of inner stator pole should be aligned with outer stator pole when \( n \) is odd while the iron rib of inner stator pole should be aligned with outer stator pole when \( n \) is even. No matter what \( n \) is selected, the rotor pole number \( N_{R} \) can be any integer except the phase number and its multiples. The analysis results indicate that the optimal \( N_{R} \) is closed to \((N_{R}+N_{\text{OS}})/2\) and it is odd when \( n \) is odd while it is even when \( n \) is even. Meanwhile, symmetrical phase back-EMF waveform will be obtained when the ratio of \( \text{Min}(N_{\text{OS}}, N_{\text{IS}}) \) to the greatest common divisor of \( \text{Min}(N_{\text{OS}}, N_{\text{IS}}) \) and \( N_{E} \) is even. Based on the optimal rotor pole numbers for 6-pole outer stator with different \( n \) and corresponding optimal relative position together with same rated copper loss, the average torque is improved by 18.4%, 25.1% and 25.7% respectively in PS-SFPMMs with \( n \) equal to 2, 3 and 4 when compared with PS-SFPMM with \( n \) equal to 1. The analyses are validated by experiment results of the prototype machine.

Index Terms—Inner/outer stator, partitioned stator, permanent magnet, pole ratio, relative position, switched flux.

I. INTRODUCTION

Switched flux permanent magnet (PM) machines (SFPMMs) have been investigated extensively over last decades due to high torque performance and efficiency as well as simple and robust rotor [1]-[22]. Since the PMs are located in the stator, easy heat dissipation and low risk of demagnetization also are the merits of SFPMMs [3]. Compared with the conventional PM brushless machines, the reluctance torque of SFPMMs is negligible [3]. Hence, the electromagnetic torque of SFPMMs is mainly depending on the PM flux-linkage, armature current (\(q\)-axis) and rotor pole number. In other words, trade-off among the PM volume (shape), armature winding space (slot area) and rotor pole number is the key factor on maximizing the torque of SFPMMs. Based on this guideline, different topologies of SFPMMs are proposed in [4]-[7]. Compared with conventional SFPMM, C-core [4] and E-core [5] SFPMMs adopt the strategy of reducing the number of PM and stator tooth to increase the slot area whilst sandwiched SFPMM (SSFPM) [6] combines two adjacent stator poles to achieve the same goal. In addition, splitting the original stator teeth into more small teeth per stator pole (reduce the slot area) and increasing the number of rotor poles are the designs which are used in multi-tooth SFPMM (MTSFPMM) [7]. Overall, the torque capability of SFPMMs is enhanced by these means under the same machine size and the same rated copper loss [8].

However, the pursuit on higher torque capability is continuing forever. In order to further enhance the torque capability of SFPMMs, one effective solution is to increase the whole volume of stator within the same machine size. Then, the concept of partitioned stator (PS) configuration is introduced and employed in the conventional SFPMMs as PS-SFPMMs [23]. The PMs and armature windings are separated into inner and outer stators respectively while the rotor is modular. In this way, the conflicts between PMs, armature windings and stator iron in conventional SFPMMs which limit the torque capability are solved in PS-SFPMMs since the inner space is fully utilized. Therefore, the torque capability is enhanced significantly in PS-SFPMMs [23]. Moreover, compared with conventional SFPMM, the fault tolerance capabilities are further enhanced in PS-SFPMMs due to the separated armature winding-stator and PM-stator as well as the stationary PMs, such as demagnetization withstand capability which caused by armature reaction and overheating.

Nevertheless, since the PMs and armature windings of PS-SFPMMs are located in two separated inner and outer stators respectively, the ratio of inner/outer stator pole number \( n \) \((n=N_{\text{IS}}/N_{\text{OS}})\) should not only be restricted to one as considering in [23] but also can be either larger or smaller than one (even suitable for all other types of stator PM machine with PS configuration). In other words, the combination of PM and stator pole (for armature windings) numbers will be more...
flexible when PS configuration is employed. The partial investigation on PS-SFPMMs with \( n=1/2 \) (PM number lower than stator pole number) is presented in [24] and the results show that it can exhibit slightly higher PM utilization efficiency but much poorer torque capability than those of PS-SFPMMs with \( n=1 \) under the optimal single-layer winding configuration. The initial investigation on PS biased flux PM machines (PS-BFPMMs) with \( n \) equal to 1, 1/2 and 2 is presented in [25] and the results show that PS-BFPMM with \( n=2 \) exhibits higher torque capability and PM utilization efficiency while PS-BFPMM with \( n=1/2 \) shows both lower values when compared with PS-BFPMM with \( n=1 \). However, the influence of relative positions between inner and outer stators under different \( n \) as well as the influence of the rotor pole number combinations is not been investigated. Meanwhile, the whole variation trend of influence caused by \( n \) is also not presented. Thus, it is necessary to compare the electromagnetic performance of PS-SFPMMs with \( n \neq 1 \), i.e. \( n<1 \) or \( n>1 \), and to comprehensive investigate the influence of \( n \).

Based on the 6-pole outer stator (armature winding-stator), the influence of inner (PM-stator)/outer stator pole ratio \( n \), corresponding relative positions and rotor pole number combinations on electromagnetic performance of PS-SFPMMs will be investigated in this paper. Firstly, the machine topologies, operational principle and optimal relative position of two stators under different \( n \) are illustrated. Then, the optimal rotor pole numbers for 6-pole outer stator machines having different \( n \) and corresponding optimal relative position are investigated under the rated copper loss. Further, based on the individual optimal rotor pole numbers, the electromagnetic performance of PS-SFPMMs with \( n \) equal to 1, 2, 3 and 4 are analyzed and compared with the optimal 8-rotor pole PS doubly salient PM machines (PS-DSPMMs) \((n=1/3)\) under the same 6-pole outer stator. Finally, a prototype machine with 12-inner/6-outer stator/10 rotor pole \((12I/6O/10R)\) PS-SFPMM is manufactured and measured to validate the analyses.

II. OPERATION PRINCIPLE AND INNER STATOR/ROTOR POLE NUMBER COMBINATIONS OF PS-SFPMMs WITH DIFFERENT \( n \)

A. Topologies and Operational Principle

Partitioned stator (PS) switched flux permanent magnet (PM) machines (PS-SFPMMs) with inner/outer stator pole ratio \( n=(N_{I}/N_{O}) \) equal to one is shown in Fig. 1(a). However, \( n \) can be any integers since the PMs and armature windings are located in separate inner and outer stators. Consequently, by way of example, several configurations of PS-SFPMMs with \( n>1 \) (PM number larger than stator pole number for armature windings) are shown in Fig. 1(b), (c) and (d) as examples, which corresponds to \( n \) equal to 2, 3 and 4 respectively.

Although the PS-SFPMMs with different \( n \) (especially for \( n \geq 1 \)) can be operated well whenever the relative position of inner and outer stators is selected, their electromagnetic performances will be affected. Therefore, to maximize the torque performance (fundamental coil flux-linkage) of PS-SFPMMs with \( n \geq 1 \), the PM of inner stator pole should be aligned with outer stator pole when \( n \) is odd while the iron rib of inner stator pole should be aligned with outer stator pole when \( n \) is even, as shown in Fig. 1 or Fig. 2. It can be evidenced by the per-unit coil flux-linkage waveforms shown in Fig. 3, which assume that the position of the PM of inner stator pole aligned with outer stator pole as an initial position \((0, \tau \) is the inner stator pole pitch) for different \( n \) (both odd and even) as well as the direction of inner stator moved from left to right (corresponding to the anticlockwise direction in rotating machine) as positive direction (+). Obviously, the highest fundamental coil flux-linkage of PS-SFPMMs with \( n \) equal to odd is obtained when the angular displacement is 0 (the PM of inner stator pole is aligned with outer stator pole) while that of PS-SFPMMs with \( n \) equal to even is achieved when the angular displacement is \(+0.5\tau\) or \(-0.5\tau\) (the iron rib of inner stator pole is aligned with outer stator pole). Moreover, with the increased number of \( n \) (for both odd and even), the differences for biased value and fundamental coil flux-linkage caused by the different relative position of inner and outer stators will be reduced gradually, as shown in Fig. 3(b) and (d).

Based on the optimal relative positions of inner and outer stators, the main PM flux paths of PS-SFPMMs with different \( n \) corresponding to the negative \( d \)-axis and positive \( d \)-axis are also illustrated in Fig. 1 and Fig. 2 respectively. It can be seen that the main flux passing through one single coil are consisted with two separate flux loops in all PS-SFPMMs with different \( n \). Meanwhile, for one complete singe flux loop of PS-SFPMMs with \( n>2 \), the flux has to pass through more than one PM, as shown in Fig. 1(c), (d), and Fig. 2(c), (d).

Furthermore, the basic operational principles of PS-SFPMMs with different \( n \) are consistent. For PS-SFPMMs with \( n \) being odd, it can be seen from Fig. 1(a) and (c) when the right edge of rotor is aligned with outer stator pole, the flux flows from inner stator side to outer stator side through the modular rotor, while in Fig. 2(a) and (c), when the left edge of rotor is aligned with outer stator pole, the direction of flux is reversed. Then, for PS-SFPMMs with \( n \) being even, it can be seen from Fig. 1(b) and (d) when the rotor slot is aligned with outer stator pole, the flux flows from inner stator side to outer...
stator side through the modular rotor, while in Fig. 2(b) and (d), when the modular rotor is aligned with outer stator pole, the direction of flux is reversed. Therefore, for PS-SFPMMs with different $n$, the back-EMF will be induced in the coils by the periodical variation of flux-linkage (flux) with rotor position.

\[ N_{OS} = km \quad (k = 1, 2, \ldots) \]  
\[ N_{IS} = nN_{OS} \quad (n = 1, 2, \ldots) \]  
\[ N_R = \mu N_{OS} \pm j \quad (N_R \neq km, j=1, 2, \ldots, k=1, 2, \ldots) \]

where $m$ is the phase number, $n$, $\mu$, $j$ and $k$ are integers.

Fig. 3. Per-unit open-circuit coil flux-linkages against different relative positions of inner and outer stators for both $n$ equal to odd and even, the base values equal to the maximum fundamental coil flux-linkages respectively.

**B. Inner Stator and Rotor Pole Number Combinations with Different $n$**

Similar to the conventional SFPMMs, the choice of rotor pole number $N_R$ is also flexible in PS-SFPMMs. No matter what $n$ is selected, $N_R$ can be any integers except the phase number and its multiples. Meanwhile, considering the investigation in this paper is focused on the PS-SFPMMs with $n \geq 1$, the selections of $N_{OS}$, $N_{IS}$ and $N_R$ can be normally summarized as

Based on the 6-pole outer stator ($N_{OS}$=6, the minimum stator pole number in unit conventional SFPMM is normally defined as 6) and the optimal relative position of inner and outer stators, the torque variations of PS-SFPMMs with different $n$ and rotor pole number under the rated 30W copper loss are shown in Fig. 4. Obviously, for PS-SFPMMs with different $n$, the maximum average torque is improved with the increased $n$. Meanwhile, PS-SFPMMs with $n$ equal to 3 and 4 have similar maximum average torque, which means the aggravated saturation and leakage flux caused by increased $n$ will also limit the enhancement of torque performance. Then, according to the maximum average torque as shown in Fig. 4 with black marks, the optimal inner stator/rotor pole combinations ($N_{IS}/N_R$) for 6-pole outer stator PS-SFPMMs with $n$ equal to 1, 2, 3 and 4 are 6I/11R (6-pole inner stator/11-pole rotor), 12I/10R, 18I/11R and 24I/14R respectively. Further, based on the results mentioned above and shown in Fig. 4, the guideline to search for the optimal $N_R$ in PS-SFPMMs with different $n$ can be roughly derived and summarized. Firstly, the optimal $N_R$ is closed to ($N_{OS}+N_{IS}$)/2. Secondly, optimal $N_R$ is odd when $n$ is odd while it is even when $n$ is even.

The topologies of 6-pole outer stator PS-SFPMMs with the
optimal 6I/11R, 12I/10R, 18I/11R and 24I/14R inner stator/rotor pole combinations for n equal to 1, 2, 3 and 4 are shown in Fig. 5. All the machines are globally optimized by genetic algorithm with the purpose of maximum average torque under the 30W rated copper loss and the same machine size. The main geometric parameters are detailed in Tab. I (OS and IS are inner stator and outer stator respectively).

C. Winding Configurations

Since the PS-SFPMMs with different n have the same operational principle of the conventional SFPMMs, their armature winding configurations can also be determined by the conventional coil-EMF phasor method [8], [23]. Consequently, for two adjacent coil-EMF phasors of PS-SFPMMs with different n, the electrical degree $\alpha_n$ can be calculated from the mechanical degree $\alpha_m$ according to (4).

$$\alpha_n = N_r \alpha_m$$  (4)

Based on (4), the winding configurations of 6-pole outer stator PS-SFPMMs with 6I/11R, 12I/10R, 18I/11R and 24I/14R inner stator/rotor pole combinations are shown in Fig. 6, Fig. 7 and Fig. 8 as mechanical and electric degrees respectively. Coil N and Coil N’ are referred to the coils with opposite polarities when accounting for the alternate magnetization directions in adjacent outer stator poles caused by the corresponding PMs in the inner stators [26], such as coils 1 and 2 shown in Fig. 7(a) and Fig. 7(c) for PS-SFPMMs with n is odd.

D. Conditions for Symmetrical Phase Back-EMF

For PS-SFPMMs with different n, symmetrical back-EMF waveform will be obtained when the ratio of $Min(N_{OS}, N_{IS})$ to the greatest common divisor of $Min(N_{OS}, N_{IS})$ and rotor pole numbers $N_R$ is even, as will be evidenced in section 2.

$$E_{even} = \frac{Min(N_{OS}, N_{IS})}{GCD(Min(N_{OS}, N_{IS}), N_R)}$$  (5)

where $GCD$ means the greatest common divisor.

III. PERFORMANCE COMPARISON BETWEEN 6-POLE OUTER STATOR PS-SFPMMs AND PS-DSPMM with OPTIMAL NIS/NR

In this section, the electromagnetic performance of 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs will be analyzed and compared with 2I/8R PS doubly salient PM machine (PS-DSPMM) under the same rated 30W copper loss ($\rho_c = 30W$) since they represent the optimal inner stator/rotor pole combinations under the same 6-pole outer stator.

Fig. 9(a) shows the topology of 6-pole outer stator PS-DSPMMs with the optimal 2I/8R inner stator/rotor pole combination ($n=1/3$) since it has the largest average torque and

![Fig. 6. Coil-EMF phasors of 6-pole outer stator PS-SFPMMs in mechanical degree.](image)

![Fig. 7. Coil-EMF phasors of 6-pole outer stator PS-SFPMMs in electric degree and sectors for determining phase winding.](image)

![Fig. 8. Phase winding (coils) configurations of 6-pole outer stator PS-SFPMMs.](image)

![Table I: MAIN PARAMETERS OF PS-SFPMMs AND PS-DSPMMs](table)
highest torque per PM volume as shown in Fig. 9(b). The main geometric parameters are also detailed in Table I.

A. Open-Circuit Field Distribution

The open-circuit flux equipotential and flux density distribution for four PS-SFPMMs and one PS-DSPMM at the negative d-axis are shown in Fig. 10. Obviously, different from the long flux path observed in PS-DSPMM, all PS-SFPMMs have short flux path which could result in lower MMF drop in the stator and thinner thickness of stator yoke. Meanwhile, the flux loops of the coils belong to same phase are completely independent in all PS-SFPMMs while those are dependent in PS-DSPMM. For both PS-SFPMMs with different n and PS-DSPMM, since the PMs are located in the inner stator, leakage flux exists inside of the inner stator but is quite small when compared with main flux. In addition, the heavy saturation in all machines is occurred at the position when the rotor nearly aligns with PMs of inner stator and has contact surface with outer stator simultaneously. It also can be reflected by open-circuit air-gap flux density waveforms at negative d-axis as shown in Fig. 11. Since the PS-SFPMMs and PS-DSPMMs both have two layers of air-gap, the waveforms are focused on the layer which close to the stator wound with AC armature winding (outer stator).

B. Flux-linkage and Back-EMF Waveforms

As shown in Fig. 12, the phase flux-linkage waveform is bipolar in all PS-SFPMMs while that is unipolar in PS-DSPMM. Meanwhile, compared with PS-DSPMM, all PS-SFPMMs exhibit significantly larger fundamental phase flux-linkages. Further, among the four PS-SFPMMs, 12I/10R and 18I/11R PS-SFPMMs have the similar highest fundamental flux-linkage, and then followed by 24I/14R and 6I/11R PS-SFPMMs respectively, as shown in Fig. 12(b) and Tab. II.

According to (5), among the four PS-SFPMMs, symmetrical phase back-EMF waveforms should be obtained in 6I/11R and 18I/11R PS-SFPMMs. It is evidenced by the waveforms and
According to (6), the cycle numbers of cogging torque for 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs with 6-pole outer stator are 6, 3, 6, and 3 respectively. These results are evidenced by the waveforms and FFT results of cogging torque shown in Fig. 15.

Fig. 13. Open-circuit phase back-EMFs of PS-SFPMMs and PS-DSPMM, 400r/min.

FFT results shown in Fig. 13 since the even harmonics which cause the asymmetric back-EMF waveform (unequal positive and negative peak values when \( n \) is odd while slant to right or left in half cycle when \( n \) is even) in the single coil are completely cancelled in the phase winding. Moreover, due to the influence of rated electrical frequency, 24I/14R PS-SFPMM exhibits the highest fundamental back-EMF among the four PS-SFPMMs, and then followed by 18I/11R, 12I/10R and 6I/11R PS-SFPMMs respectively, as shown in Fig. 13(b) and Tab. II. Further, compared with 2I/8R PS-DSPMM, 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs have 221%, 289%, 325% and 331% higher fundamental phase back-EMFs.

C. Axis Inductances

The \( dq \)-axis inductances against current angle for all machines at rated currents (corresponding to \( p_c = 30W \)) are compared in Fig. 14. It can be seen that the \( dq \)-axis inductances of PS-SFPMMs are raised with the increase of \( n \). Meanwhile, the \( q \)-axis inductances are slightly larger than \( d \)-axis inductances when current angle close to 0° but reversed when current angle close to 90°. Further, the saliency ratios of PS-SFPMMs with different \( n \) and PS-DSPMM are all close to 1 since differences between \( dq \)-axis inductances are all quite small. Hence, the potential reluctance torque can be negligible in all PS-SFPMMs with different \( n \) and PS-DSPMM.

D. Cogging Torque

Fig. 15 shows the cogging torque waveforms of all machines. Obviously, among the four PS-SFPMMs, 12I/10R PS-SFPMM exhibits the largest magnitude of cogging torque while 18I/11R PS-SFPMM has the smallest value. Moreover, PS-DSPMM has larger cogging torque than all PS-SFPMMs.

For PS-SFPMMs with different \( n \), the cycle number of cogging torque over one electric period (\( N_c \)) can be defined as

\[
N_c = \frac{\text{MIN}(N_{LS}, N_{OS})}{\text{GCD}(\text{MIN}(N_{LS}, N_{OS}), N_R)}
\]  

Fig. 14. Variation of \( dq \)-axis inductances with current angle under the rated currents of all machines as given in Tab. I, \( p_c = 30W \).

Fig. 15. Open-circuit cogging torque of PS-SFPMMs and PS-DSPMM.

E. Electromagnetic Torque Characteristics

The waveforms of average torque against current angle at rated currents (\( p_c = 30W \)) for all machines are shown in Fig. 16. Obviously, the reluctance torque can be negligible in both PS-SFPMMs with different \( n \) and PS-DSPMM since the optimal current angles are all close to 0°. These results are consistent with the conclusion mentioned in section 2.3.

Fig. 16. Variation of average torque with current angle under the rated currents for all PS-SFPMMs and PS-DSPMM as given in Tab. I, \( p_c = 30W \).
PS-SFPMMs are 6, 3, 6 and 3 respectively while that for 2I/8R PS-DSPMM is 1. Further, as shown in Tab. II, the torque ripples of 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs and 2I/8R PS-DSPMM are 2.1%, 26.9%, 3.6%, 20.4% and 135.2% respectively. Obviously, among the four PS-SFPMMs, 6I/11R PS-SFPMM exhibits the smallest torque ripple while 12I/10R PS-SFPMM has the largest one. Meanwhile, all PS-SFPMMs exhibit much lower torque ripples than that of PS-DSPMM.

As shown in Table II, the average torques for 6I/11R \((n=1)\), 12I/10R \((n=2)\), 18I/11R \((n=3)\), 24I/14R \((n=4)\) PS-SFPMMs and 2I/8R \((n=1/3)\) PS-DSPMM under the rated current \((p_r=30W)\) are 4.47, 5.29, 5.59, 5.62 and 1.41Nm respectively. Compared with the optimal 6-pole outer stator PS-SFPMMs with \(n\) equal to 1, the maximum torque capability is enhanced by 18.4%, 25.1% and 25.7% respectively in the optimal 6-pole outer stator PS-SFPMMs with \(n\) equal to 2, 3, and 4. Moreover, 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs exhibit \(\sim 217\%\), \(275\%\), \(296\%\) and \(299\%\) larger average torque respectively than that of 2I/8R PS-DSPMM.

Fig. 18 compares the torque density and torque per PM volume of all machines at the rated currents \((p_r=30W)\) and \(I_f=0\) control. Obviously, for PS-SFPMMs, as \(n\) increases, the torque density is enhanced whilst the torque per PM volume (PM utilization efficiency) is decreased. As shown in Tab. II, the torque densities for 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs are 28.1, 33.3, 35.1 and 35.4 kNm/m³ respectively. Since four PS-SFPMMs have the same machine size, the increase rates of torque density caused by the increased \(n\) are consistent with those of average torque. Then, the PM utilization efficiency for 6I/11R, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs are 297, 224, 219 and 211 kNm/m³ respectively. Compared with the optimal 6-pole outer stator PS-SFPMMs with \(n\) equal to 2, 3, and 4. Moreover, 2I/8R PS-DSPMM \((n=1/3)\) exhibits much lower torque density than all PS-SFPMM with \(n \geq 1\) but slightly higher PM utilization efficiency than PS-SFPMM only with \(n \geq 3\).

The variations of average torque with the current and copper loss are further shown in Fig. 19 and Fig. 20 respectively. Compared with 6I/11R PS-SFPMM, 12I/10R, 18I/11R and 24I/14R PS-SFPMMs exhibit higher average torque under same current/cooper loss over the whole current/cooper loss ranges. This result indicates that PS-SFPMMs with \(n=1\) can enhance the torque performance not only in low electric loading but also in high electric loading. Further, compared with
18I/11R PS-SFPMM, the average torque of 24I/14R PS-SFPMMs is slightly larger at relatively low copper loss (lower than 40W) but smaller at high copper loss (higher than 40W) due to the more severe saturation and leakage flux. In addition, during the whole current/copper loss range, all PS-SFPMMs exhibit much higher average torque than that of PS-DSPMM.

IV. EXPERIMENTAL VERIFICATION

Prototype machine of 12I/10R PS-SFPMM with 6-pole outer stator is made to validate the foregoing analyses, as shown in Fig. 21. Existing inner stator with 12 PMs and 10-pole rotor are used for experiment, and new 6-pole outer stator is made according to the re-optimized results. Therefore, the parameters of prototype machine as shown in Table III are different from the previous globally optimized parameters as given in Tab. I.

In addition, for easing the fabrication, lamination bridges with 0.5mm thickness ($TB_{RI}$) are added to both top and bottom edges of PMs to help fixing, as shown in Fig. 21(b). Meanwhile, 10-pole segment rotor is mechanically connected by lamination bridges in the inner side, as shown in Fig. 21(d).

![Fig. 21. Prototype of 12I/10R PS-SFPMM with 6-pole outer stator.](image)

**Fig. 21.** Prototype of 12I/10R PS-SFPMM with 6-pole outer stator.

<table>
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<tr>
<th>Parameter</th>
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![Fig. 22. Measured and FE predicted phase back-EMFs at 400r/min.](image)

**Fig. 22.** Measured and FE predicted phase back-EMFs at 400r/min.

![Fig. 23. Measured and FE predicted open-circuit cogging torques.](image)

**Fig. 23.** Measured and FE predicted open-circuit cogging torques.

![Fig. 24. Measured and FE predicted static torques, $I_{ax}=l_{x}-2l_{y}=-2I_{c}$.](image)

**Fig. 24.** Measured and FE predicted static torques, $I_{ax}=l_{x}-2l_{y}=-2I_{c}$.

![Fig. 25. Measured and FE predicted peak torque–current characteristics waveforms.](image)

**Fig. 25.** Measured and FE predicted peak torque–current characteristics waveforms.

Fig. 22 shows the measured and predicted phase back-EMF at rated speed (400rpm). Due to the end-effect in 25mm stack length machines, the measured fundamental value is ~8% less than the prediction. Meanwhile, the amplitude of measured 5th harmonic is lower than that of FE prediction but higher for 2nd harmonic, which is caused by the imperfect manufacture. The
measured and predicted open-circuit cogging torque waveforms are compared in Fig. 23. Since the partitioned stator machine has three components, the assembly process of prototype is more complicated and easier to introduce errors, such as rotor eccentricity, inner/outer stator positions, etc. The difference as shown in Fig. 23 may be caused by the imperfect installation of the prototype. Considering the measurement error and end-effect, the measured peak to peak value agrees well with the FE prediction and the waveforms are relatively consistent. Fig. 24 shows the waveforms of static torque with rotor position at three different armature currents, i.e. 15A, 20A and 25A (\(I_{dc}=1\), \(I_{ac}=2\)). Furthermore, the measured and predicted peak torques corresponding to different currents are compared in Fig. 25. It can be seen that the differences between the measured and FE predicted results enlarge with increased current due to the more severe end effect caused by saturation. In general, the measured results agree well with the FE predictions.

V. CONCLUSIONS

In this paper, the influence of inner/outer stator pole ratio \(n\), corresponding relative positions and rotor pole number combinations on electromagnetic performance of PS-SFPMMs is investigated based on the 6-pole outer stator.

To maximize the torque performance of PS-SFPMMs with \(n \geq 1\), the PMs of inner stator pole should be aligned with outer stator pole when \(n\) is odd while the iron rib of inner stator pole should be aligned with outer stator pole when \(n\) is even. No matter what \(n\) is selected in PS-SFPMMs, the choice of rotor pole number \(N_R\) is flexible and can be any integers except the phase number and its multiples. The analysis results indicate that the optimal \(N_R\) is closed to \((N_{ac}+N_{gs})/2\) and it is odd when \(n\) is odd while it is even when \(n\) is even. Meanwhile, symmetrical phase back-EMF waveform will be obtained when the ratio of \(\min(N_{ac}, N_{gs})\) to the greatest common divisor of \(\min(N_{ac}, N_{gs})\) and \(N_R\) is even. Further, 6I/11R, 12I/10R, 18I/11R and 24I/14R are the optimal inner stator/rotor combinations of 6-pole outer stator PS-SFPMMs with \(n\) equal to 1, 2, 3 and 4 respectively. Compared with 6I/11R (\(n=1\)) PS-SFPMM under the same rated copper loss and the same machine size, the average torque is improved by 18.4\%, 25.1\% and 25.7\% respectively for 12I/10R (\(n=2\)), 18I/11R (\(n=3\)) and 24I/14R (\(n=4\)) PS-SFPMMs. Since PS-SFPMMs with \(n\) equal to 3 (5.59Nm) and 4 (5.62Nm) have similar maximum average torque, it means that the aggravated saturation and leakage flux caused by increased \(n\) will also limit the enhancement of torque performance. Among these four PS-SFPMMs, 6I/11R and 18I/11R PS-SFPMMs exhibit more symmetrical phase back-EMF, smaller coggging torque and lower torque ripple. Moreover, PS-DSPMM (\(n=1/3\)) exhibits much lower torque density than all PS-SFPMMs with \(n \geq 1\) but slightly higher PM utilization efficiency than PS-SFPMM only with \(n \geq 3\). The analyses have been validated by both the FEA and measurements.

REFERENCES


**Juntao Shi** received the B.Eng. degree in electrical engineering and automation from Taiyuan University of Technology, Taiyuan, China, in 2008, and the M.Sc. and Ph.D. degrees in electronic and electrical engineering from The University of Sheffield, Sheffield, U.K., in 2011 and 2016, respectively. From 2016 to 2017, he was a research associate in Department of Electrical and Electronic Engineering, Newcastle University, Newcastle, UK. Since 2017, he has been with the U.K. Research Centre, IMRA Europe S.A.S., Brighton, U.K., where he is currently a senior research engineer. His major research interests include the advanced electrical machines and drives for automotive application.

**Z. Q. Zhu** received the B.Eng. and M.Sc. degrees from Zhejiang University, Hangzhou, China, in 1982 and 1984, respectively, and the Ph.D. degree from the University of Sheffield, Sheffield, U.K., in 1991, all in electrical engineering. Since 1988, he has been with the University of Sheffield, where since 2000, he has been a Professor with the Department of Electronic and Electrical Engineering. He is currently the Royal Academy of Engineering/Siemens Research Chair, and the Head of the Electrical Machines and Drives Research Group, the Academic Director of Sheffield Siemens Wind Power Research Centre, the Director of CRRC Electric Drives Technology Research Centre, and the Director of Midea Electric Machines and Controls Research Centre. His current major research interests include the design and control of permanent magnet brushless machines and drives for applications ranging from electric vehicles through domestic appliance to renewable energy. He is a Fellow of Royal Academy of Engineering, U.K., a Fellow of Institute of Electrical and Electronics Engineers, U.S.A., and a Fellow of Institute of Engineering and Technology (IET), U.K.