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Design Guidelines for Fractional Slot Multi-Phase Modular Permanent Magnet Machines

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Abstract: This paper presents the design considerations for a fractional slot multi-phase modular permanent magnet (PM) machine with single-layer concentrated windings. The winding factors for various slot/pole number combinations are calculated to identify the optimal slot/pole number combinations for different phase numbers. In addition, the electromagnetic performance influenced by flux gaps (FGs), such as air-gap MMF, back-EMF, cogging torque, on-load torque and torque ripple, etc., are comprehensively investigated by using the 2-D finite element (FE) method. Several general rules with respect to the influence of FGs on multi-phase modular PM machines performance are established. The prototypes of modular PM machines are built and the finite element results are validated with experiments.

1. Introduction

PERMANENT magnet (PM) machines have been increasingly applied to many applications such as electric and hybrid vehicles, aerospace actuation and renewable energy, eg. wind power generators, due to their inherent advantages, including high torque density and efficiency. [1]-[3]. However, for some safety-critical applications such as offshore wind power, the PM machines are not only required to have excellent performance (high torque and efficiency) but also good fault-tolerant capability. To achieve such capability, the single-layer concentrated winding layouts [4] are often employed, which can reduce the short-circuit current and limit the fault propagation between phases. In addition, multi-phase (>3) machines can also be employed, which provide extra freedom when dealing with the faults such as armature phase open-circuit or short-circuit [5].

There are many inherent advantages offered by multi-phase machines, eg. the improvement on reliability, the reduction in the phase current without the increase in phase voltage, and the mitigation of the torque ripple, etc. [6]. The influence of phase number on the winding factors, cogging torque frequency and net radial forces are comprehensively investigated in [7], which also provides guidelines for selecting the optimal slot/pole number combinations for multi-phase PM machines. Five-phase [8]-[12], six-phase[13]-[15] and dual three-phase [16]-[17] machines (similar to six-phase machines) are the most widely studied multi-phase machines in the existing literature. In [17], a novel dual three-phase, 78-slot/12-pole PM synchronous motor with asymmetric stator winding is proposed (phase shift angle between phases A and B is 120.3 Elec. Deg. rather than 120 Elec. Deg. in conventional symmetrical machines) in order to achieve good performance and lower MMF harmonic contents. It is shown that the proposed dual 3-phase (multi-phase) PM machine offers extremely low cogging torque and torque ripple and also very low back-EMF total harmonic distortion. Furthermore, the torque density can be slightly improved compared with that of the dual 3-phase, 72-slot/12-pole PM machines with symmetrical windings.

Alternatively, modular topologies with single layer concentrated windings, such as those shown in Fig. 1, can also be employed to improve the fault-tolerant capabilities. Due to the fact that the segments are separated physically and magnetically in modular machines, the faults would not propagate from one segment to another. This can reduce the short-circuit current and weaken the fault interaction between phases. Hence, the modular machines are excellent options for safety-critical applications as well. There are three advantages to employing the modular structures: 1) the manufacturing process can be greatly simplified especially for the winding process [18]-[19]; 2) maintenance can be simplified because instead of having to change the entire machine, one can simply replace the faulty segment; 3) the cooling capability can be improved because the flux gaps can be used as water ducts providing extra freedom for cooling [20].

Given the previously mentioned advantages of modular machines over their conventional non-modular counterparts, they are attracting growing attention in recent years. Spooner *et al* have introduced a new type of modular machine for wind turbine applications in [21]. The proposed modular machine not only has a modular stator but also a modular rotor. This can reduce the active mass of the machines and slightly increase their efficiency compared to their non-modular counterparts with the same machine dimensions. Several similar modular structures with flux barriers in stator teeth are reported in [22]. By doing so, the stator core is segmented by the flux barriers and forms modular stator structures. In [23], a new stator design by employing flux barriers in the stator yoke to reduce or even cancel sub-harmonics in airgap flux density is proposed. It shows that the new stator design results in more than 60% reduction in sub-harmonics, remarkable core loss reduction and high flux-weakening capability.

A novel 3-phase modular surface mounted PM (SPM) machine in which the flux-gaps (FGs) are inserted into the alternate stator teeth while the single layer winding are wound on the stator teeth without flux gaps is proposed in [24]. This is shown in Fig. 1, where w_{tb} represents the tooth body width. Similar novel modular PM machines with stator tooth tips have been presented in [25]. The electromagnetic performance of the proposed modular PM machines such as air-gap flux density, phase back-EMF, cogging torque, on-load torque, copper and iron losses, etc., accounting for the influence of FGs, have been comprehensively investigated and some general rules for modular PM machines with different slot/pole number combinations have been established. It was found that the FGs between the stator segments have negative effects on the modular PM machines with a slot number higher than the pole number, eg. the average torque is reduced. On the contrary, when the slot number is lower than the pole number, the electromagnetic performance can be improved by choosing a proper flux gap width, eg. the average torque can be increased while cogging torque and torque ripple can be reduced, as are the machine iron losses.

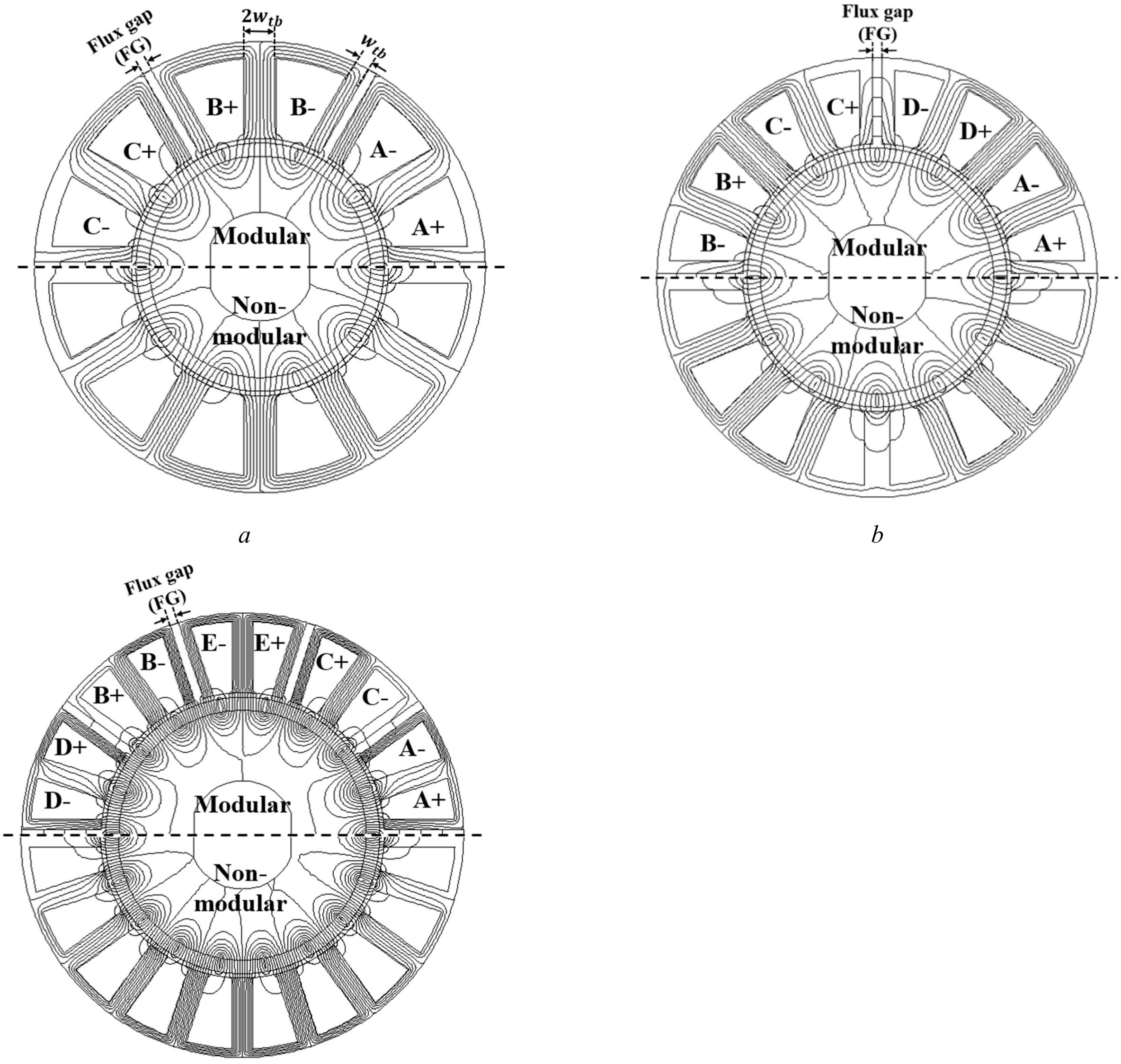

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Fig. 1. *Cross sections of modular and non-modular PM machines with open-circuit flux distributions.*
a 3-phase 12-slot/10-pole [24]
b 4-phase 16-slot/12-pole
c 5-phase 20-slot/18-pole

Nevertheless, the available literature is only focused on 3-phase modular PM machines and very few studies of multi-phase modular PM machines have been carried out. Therefore, to fill in this gap, the multi-phase modular PM machines having different slot/pole number combinations and single-layer concentrated windings will be investigated, with a particular focus on the electromagnetic performance such as air-gap armature MMF, torque, etc. Consequently, some general rules which can cover the influence of FGs on the multi-phase modular PM machines will be established and can be used as design guideline for modular machines in practice.

2. Winding Arrangements of Multi-phase Modular PM Machines

In this section, the optimal slot/pole number combinations for each modular PM machine with different phase number will be identified first so as to achieve the highest winding factor which is calculated based on its non-modular counterpart. Then, the influence of FGs on the winding factors of multi-phase modular PM machines having different slot/pole number combinations will be investigated.

2.1. Winding Factors of Non-modular PM Machines

For classic non-modular and equal teeth PM machines, without considering the higher order harmonics, the distribution factor (k_d), the pitch factor (k_p), and hence the winding factor (k_w) can be calculated by:

$$k_d = \frac{\sin(\frac{q\sigma}{2})}{q\sin(\frac{\sigma}{2})} \tag{1}$$

$$k_p = \sin(\frac{\tau_s}{\tau_p}\frac{\pi}{2}) = \sin(\frac{p\pi}{N_s}) \tag{2}$$

$$k_w = k_d \times k_p \tag{3}$$

where q is the number of coil per phase, σ is the angular phase angle between adjacent EMF vectors of one phase (in Elec. Deg.), $\tau_p = 2\pi/(2p)$ which equals to pole pitch and the slot pitch $\tau_s = 2\pi/N_s$. Additionally, N_s is the slot number while p is the rotor pole pair number. As it is well established that k_p depends on the slot/pole number combination rather than on the phase number. Therefore, the calculation of winding factor is focused on the calculations of distribution factors for fractional slot PM machines with different phase numbers.

Since the multi-phase PM machines studied here have single-layer concentrated windings, the theory developed in [26] for a double-layer concentrated winding structure is no longer applicable, therefore certain modifications have to be taken into account. The improved method is detailed as follows:

- When phase number is odd (1, 3, 5, 7, …)

$$\begin{cases} k_d = \dfrac{\sin\left(\frac{q_{ph}}{2} \times \frac{\sigma_{ph}}{2}\right)}{\left(\frac{q_{ph}}{2}\right)\sin\left(\frac{\sigma_{ph}}{2}\right)} & For\ q_{ph}\ is\ even \\ k_d = \dfrac{\sin\left(q_{ph} \times \frac{\sigma_{ph}}{4}\right)}{\left(q_{ph}\right)\sin\left(\frac{\sigma_{ph}}{4}\right)} & For\ q_{ph}\ is\ odd \end{cases} \tag{4}$$

with

$$q_{ph} = \frac{(\frac{N_s}{2})}{m \times t} \tag{5}$$

$$\sigma_{ph} = \frac{2\pi}{N_s/(2t)} \tag{6}$$

- When phase number is even (2, 4, 6, …)

$$\begin{cases} k_d = \dfrac{\sin\left(q_{ph} \times \dfrac{\sigma_{ph}}{2}\right)}{q_{ph}\sin\left(\dfrac{\sigma_{ph}}{2}\right)} & For\ \sigma_{ph} \neq \dfrac{360}{m} \\ k_d = 1 & For\ \sigma_{ph} = \dfrac{360}{m} \end{cases} \tag{7}$$

where m is the phase number, t is the greatest common divisor between the slot number divided by 2 (single layer winding) and the pole pair number. This means that the machine is composed by t elementary machines with a slot number of $\frac{N_s}{2t}$ and a pole pair number of $\frac{p}{t}$. q_{ph} is the number of slot vectors which form one phase of the elementary machine while σ_{ph} is the electrical angle between two adjacent back-EMF vectors.

By using the above method, the winding factors for fractional slot single-layer concentrated winding modular machines with different phase numbers have been calculated, and hence, the optimal slot/pole number combinations for each phase number can be determined accordingly. The results are shown in Table 1, in which only the results for each phase number with its relevant minimum achievable slot number have been given.

Table 1 Winding factors of single layer concentrated winding N-phase machines with non-modular stators

$2p \backslash N_s$	**1-phase** 4	**2-phase** 8	**3-phase** 12	**4-phase** 16	**5-phase** 20	**6-phase** 24
2	0.707	0.271	0.259	0.180	0.156	0.126
4	**1**	**0.707**	0.500	0.383	0.309	0.259
6	0.707	0.653	-	0.513	0.454	-
8	0	-	0.866	-	0.5878	-
10	-0.707	0.653	**0.966**	0.768	-	0.588
12	-1	**0.707**	-	**0.924**	0.809	-
14	-0.707	0.271	**0.966**	0.906	0.891	0.766
16	0	-	0.866	-	0.951	-
18	0.707	-0.271	-	0.906	**0.988**	-
20	**1**	-0.707	0.500	**0.924**	-	**0.966**
22	0.707	-0.653	0.259	0.768	**0.988**	0.958
24	0	-	-	-	0.951	-
26	-0.707	-0.653	-0.259	0.513	0.891	0.958
28	-1	-0.707	-0.500	0.383	0.809	**0.966**

Based on the previous results, it can be concluded that in order to achieve the maximum winding factors for fractional slot modular PM machines with different phase numbers and different slot/pole number combinations, the following rules should be satisfied:

$$N_s = 2p \qquad For\ m = 1 \tag{8}$$

$$N_s = 2p \pm 4d \qquad For\ m\ is\ even \tag{9}$$

$$N_s = 2p \pm 2d \qquad For\ m\ is\ odd \tag{10}$$

where d is an integer and equal to $N_s/(4m)$. By way of example, for 3-phase machines with 12-slot, the pole numbers enabling the machines to have their maximum winding factor are 10-pole and 14-pole; for 4-phase machines with 16-slot, the pole numbers are 12-pole and 20-pole; for 5-phase machines with 20-slot, the pole numbers are 18-pole and 22-pole. Therefore, the slot/pole number combinations mentioned above are chosen for modular PM machines with different phase numbers in order to analyse the influence of FGs on the machine's electromagnetic performance.

2.2. Winding Factors for Modular PM Machines

The winding factors for modular machines can be calculated using similar methods as those for classic non-modular machines. However, when the FGs are inserted into the alternate stator teeth, the coil pitch and hence the fundamental pitch factors (k_p) need to be modified with the variation of the flux gap widths (β_{FG}). According to [24], the pitch factor accounting for the influence of FGs can be calculated by:

$$k_p = \sin(\frac{(\tau_s - \Delta)}{\tau_p}\frac{\pi}{2}) \tag{11}$$

$$\Delta = \sin^{-1}(\frac{\beta_{FG}}{2 \times R_i}) \tag{12}$$

where R_i , τ_s and τ_p are stator inner radius, coil pitch and pole pitch, respectively. The flux gaps will reduce the coil pitch but they do not influence the pole pitch. Therefore, they will increase the pitch factor for machines with $N_s < 2p$, while reducing it for machines with $N_s > 2p$.

Since the distribution factors are unchanged due to the fixed back-EMF and slot vectors distributions for a given slot/pole number combination, the resultant winding factors of modular PM machines with different phase numbers are only affected by the pitch factors, as shown in Fig. 2.

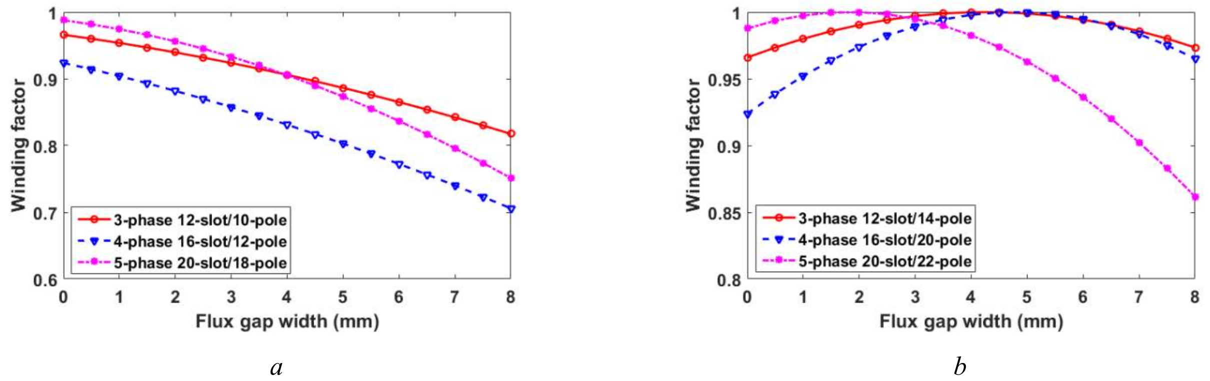


Fig. 2. *Winding factors versus flux gap width of 3-phase, 4-phase and 5-phase modular PM machines with different slot/pole number combinations.*
a $N_s > 2p$
b $N_s < 2p$

It is evident from Fig. 2 that for multi-phase modular PM machines having $N_s > 2p$, the winding factors decrease with the increase in FG width. Whereas, when multi-phase modular PM machines having $N_s < 2p$, their winding factors increase with the increasing FG width until they reach parity and subsequently decrease. The winding factor largely determines the electromagnetic performance. Therefore, the influence of FGs will also be reflected on the machine's performance, and will be investigated in the following sections.

3. Design of Modular PM Machines

The cross sections of modular PM machines with different phase numbers are depicted in Fig. 1. The rotors for all machines have surface-mounted, full arc permanent magnets although other rotor topologies can be employed such as interior or inset permanent magnets. Furthermore, it is worth mentioning that the total active tooth body width for the stator teeth with or without FGs is unchanged for different FG widths, as shown in Fig. 1. This is to avoid heavy local magnetic saturation occurring in the tooth bodies when large FGs are employed. Some of the general design parameters are exactly the same for the modular PM machines having different slot/pole number combinations and phase numbers, as shown in Table 2.

Some other design parameters are optimized individually in a certain sequence, eg. split-ratio (ratio of stator inner diameter to stator outer diameter) → tooth body width (w_{tb}) → stator yoke height (h_{sy}). The optimized design parameters for each modular PM machine with a different phase number are given in Table 3. It is worth mentioning that the stator outer diameter and active length of the 3, 4 and 5-phase modular PM machines are always the same during the optimization process.

Table 2 General design parameters of modular PM machines

Phase voltage (V)	36	Stack length (mm)	50
Rated torque (Nm)	5.5	Air-gap length (mm)	1
Rated speed (rpm)	400	Magnet thickness (mm)	3
Stator outer radius (mm)	50	Magnet remanence (T)	1.2
Filling factor k_b	0.37	Number of turns per phase	132

Table 3 Optimized design parameters of modular PM machines for achieving similar output torque

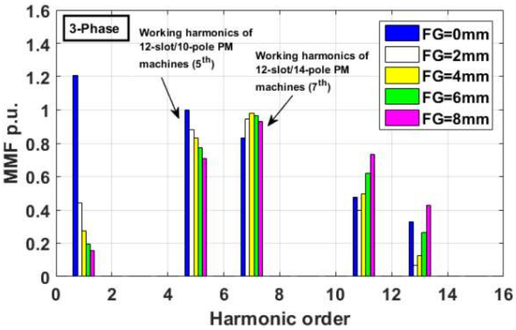
Modular PM machines	λ_s	w_{tb} (mm)	h_{sy} (mm)	I_{RMS} (A)
3-phase	0.57	7.1	3.7	7.35
4-phase	0.61	5.9	2.7	4.83
5-phase	0.64	4.7	1.9	3.41

4. Electromagnetic Performance of Modular PM Machines

4.1. Armature Magneto-Motive Force (MMF)

Although the fractional slot single-layer concentrated winding has advantages as mentioned above, the inherent drawbacks of such a winding layout cannot be overlooked. By way of example, the rich sub-harmonics in the armature MMF in the air-gap will result in many undesirable effects on the performance of PM machines, such as increasing PM eddy current loss and core losses, heavy local saturation, acoustic noise and vibrations, etc. Fortunately, the modular structure can help to effectively mitigate those MMF sub-harmonics as will be demonstrated in this section.

The harmonics of armature MMF for modular PM machines having different slot/pole number combinations and different phase numbers have been calculated. The results of the 3-phase, 4-phase and 5-phase machines are shown in Fig. 3. It has been established that the working (or fundamental) harmonics are 5th or 7th order harmonics depending on slot/pole number combination for 3-phase, 6th or 10th for 4-phase, and 9th or 11th for 5-phase machines. As shown in Fig. 3, when the flux gap width changes, the variations of the working harmonics, which produce the electromagnetic torque, are similar to those of the winding factors. This is mainly due to the fact that the working air-gap MMF is largely determined by the winding factor.



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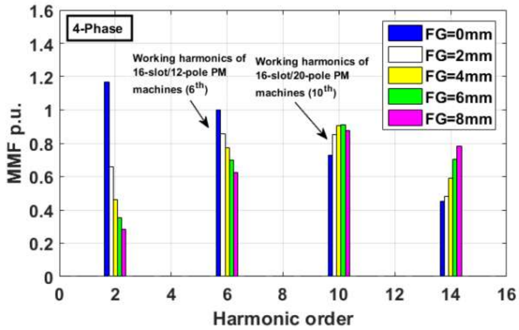

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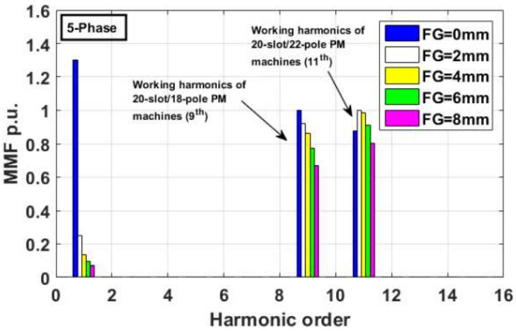

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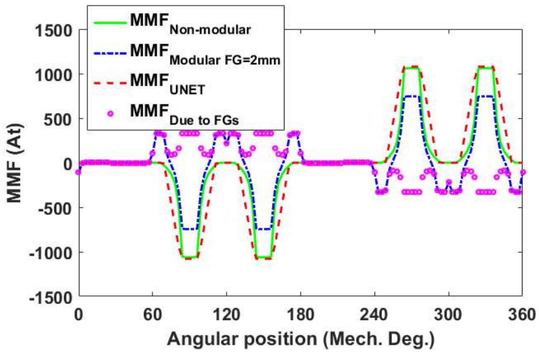
Fig. 3. *Spectra of armature MMF of modular SPM machines.*
a 3-phase modular PM machines
b 4-phase modular PM machines
c 5-phase modular PM machines

However, for 3-phase and 5-phase modular PM machines, the sub-harmonics are mainly contributed by the 1st order harmonic, while for 4-phase modular PM machines the 2nd order harmonic is the main sub-harmonic. It is evident that for all modular machines, regardless of slot/pole number combination and phase number, the main sub-harmonics are significantly reduced when the FGs are introduced into the alternate stator teeth. In order to understand the influence of FGs on the armature MMF in air-gap of modular PM machines, it is necessary to separate the influence of FGs from that of slot openings (SOs). This is because for the modular PM machines, the primary two factors that influence the armature MMF in air-gap are the SOs and FGs, as can be described by (13). Here, the corresponding non-modular PM machines with unequal teeth (UNET) are introduced, which can be simply obtained by replacing the FGs (air) by iron. This gives an armature MMF component due to SOs only (MMF_{UNET}). As a result, the MMF due to FGs only can be obtained by using the resultant MMF and subtracting the MMF_{UNET}. This is possible because, to calculate the armature MMF in the air-gap, the PMs are removed and the magnetic saturation can be neglected due to the large air-gap length of the surface mounted permanent magnet machine.

$$MMF_{modular} = MMF_{UNET} + MMF_{FGs} \tag{13}$$

Fig. 4 depicts the MMF components (due to SOs, FGs and resultant MMF) of non-modular and modular PM machines. For the latter, a 3-phase machine with 12-slot/10-pole and FG=2mm is shown as an example. It is evident that the FGs significantly reduce the subharmonics while increasing the working harmonics when the slot/pole number combination is properly selected. This is because the subharmonic component caused by FGs is always negative while for certain working harmonics, eg. the 7th order, the component due to FGs can be positive.



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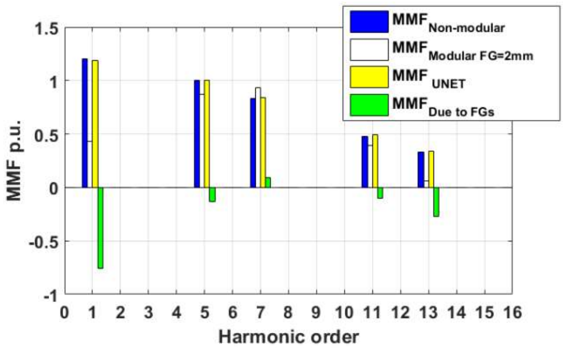

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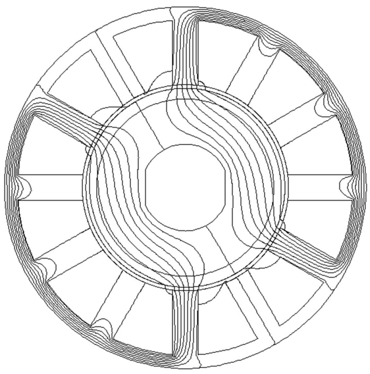
Fig. 4. *Influence of FGs on the air-gap MMF of 3-phase modular PM machines.*
a Waveforms
b Spectra

In order to further investigate the influence of FGs on the main air-gap MMF sub-harmonics, the flux distribution due to armature currents for 3-phase, 4-phase non-modular and modular PM machines are shown in Fig. 5. The 5-phase machines are not shown because its main subharmonic is similar to that of 3-phase machines. As expected, the main armature MMF subharmonic for the 3-phase machine is 2 poles, while for the 4-phase machines it is 4-poles regardless of whether the machines are modular or not. However, when the modular structure is employed as shown in Fig. 5 (c) and (d), the FGs in the stator teeth add extra equivalent air-gap length to the flux path of the main armature subharmonic MMF compared to its non-modular counterparts [Fig. 5 (a) and (b)]. As a result, the main sub-harmonics of air-gap MMF for modular PM machines with different phase numbers can be significantly reduced, as shown in Fig. 3



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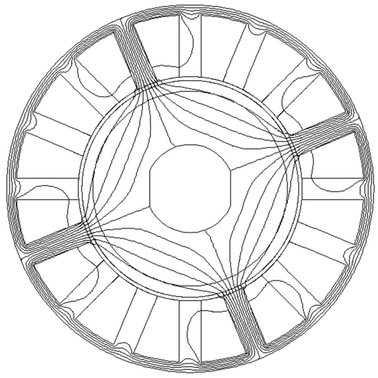

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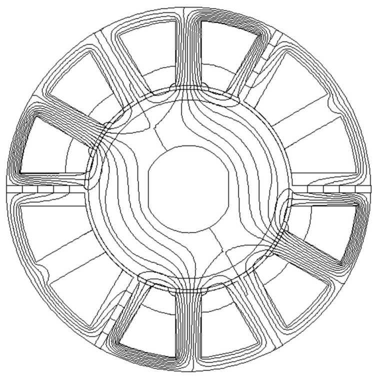

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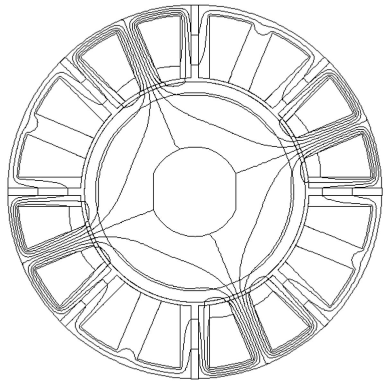

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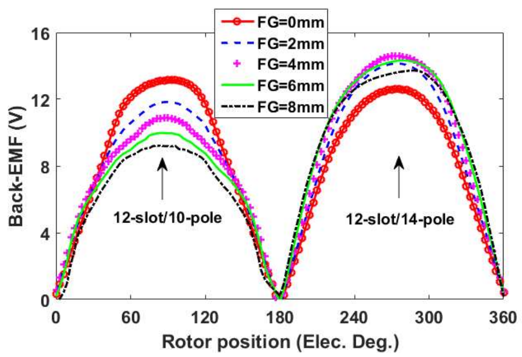
Fig. 5. *Flux distribution due to armature winding only (3-phase and 4-phase).*
a-b Non-modular PM machines
c-d Modular PM machines

4.2. Phase Back-EMF

The phase back-EMF waveforms and their spectra for modular PM machines with different phase numbers (5-phase is not shown here due to the limited space) and FG widths are shown in Fig. 6. Only the results of phase A are presented. It is found that for multi-phase modular PM machines having $N_s > 2p$, the fundamental phase back-EMFs always decrease with the increase in FG width. When $N_s < 2p$, the fundamental phase back-EMF harmonics can be improved by appropriately selecting the FG width. Such features are similar to the air-gap MMF performance as discussed in section 4.1, and are mainly due to the influence of FGs on winding factors.



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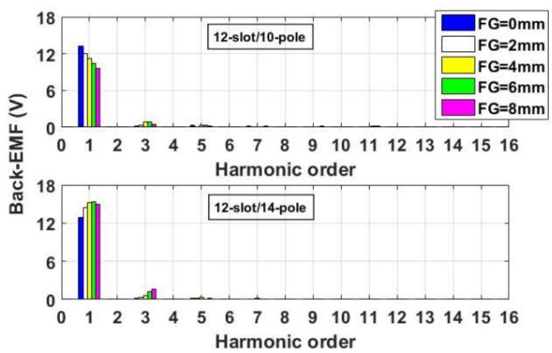

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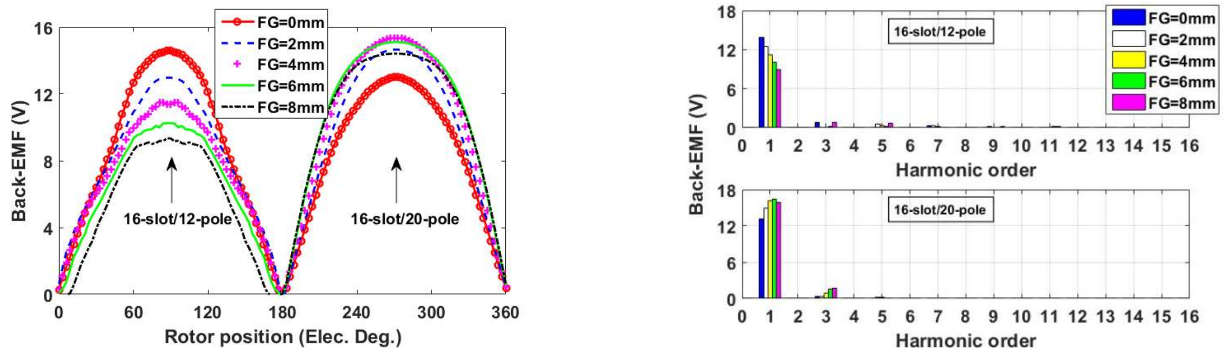


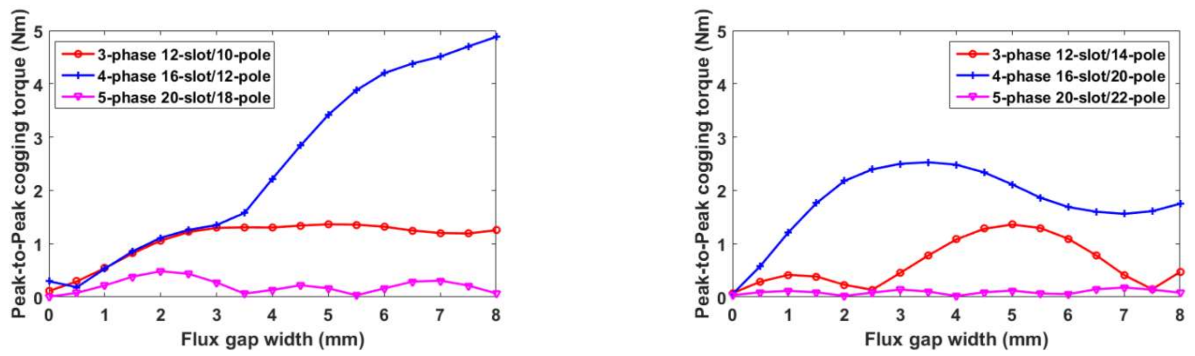
c *d*

Fig. 6. *Back-EMF waveforms and spectra.*
a-b 3-phase modular PM machines
c-d 4-phase modular PM machines

4.3. Cogging Torque

It has been established in [27] that, the periodicity and the amplitude of cogging torque for non-modular PM machines mainly depend on the value of N_c, which is the least common multiple (LCM) between the N_s and the $2p$. The higher the N_c is, the lower the cogging torque will be. However, when the modular structure is employed, the value of N_c becomes N_{cm} due to the change in stator core symmetry. N_{cm} can be obtained by calculating the LCM between $2p$ and the number of FGs [28].

By way of example, the optimal slot/pole number combinations to achieve the highest winding factor for 4-phase modular PM machines are 16-slot/12-pole and 16-slot/20-pole and the number of FGs is 8. Hence, the values of N_{cm} are 48 and 40, respectively. However, for 5-phase modular PM machines, the optimal slot/pole number combinations are 20-slot/18-pole and 20-slot/22-pole and the FG number is 10, leading to N_{cm} of 90 and 110, respectively. As a result, the peak-to-peak cogging torques of 4-phase modular PM machines are always higher than those of 5-phase modular PM machines, as shown in Fig. 7. Moreover, for different multi-phase machines, if the slot/pole number combination and FG width are properly selected, the peak-to-peak cogging torque can be significantly reduced. This will have a profound impact on the torque ripple as will be investigated in the following section.



a *b*

Fig. 7. *Peak-to-peak cogging torque of modular PM machines with different phase numbers.*
a $N_s > 2p$
b $N_s < 2p$

4.4. On-load Torque and Torque Ripple

The results of average torque and torque ripple of modular PM machines with different phase numbers and supplied by sinusoidal waveform currents (the phase RMS currents are given in Table 3) are shown in Fig. 9. It can be found that the average torques of the modular PM machines having $N_s > 2p$**,** decrease with the increasing flux gap width regardless of phase number. However, for the modular PM machines having $N_s < 2p$, the average torques can be maximized by selecting appropriate FG widths. This is mainly due to the impacts of FGs on the armature MMF working harmonics and the fundamental harmonics of phase back-EMFs, as detailed previously.

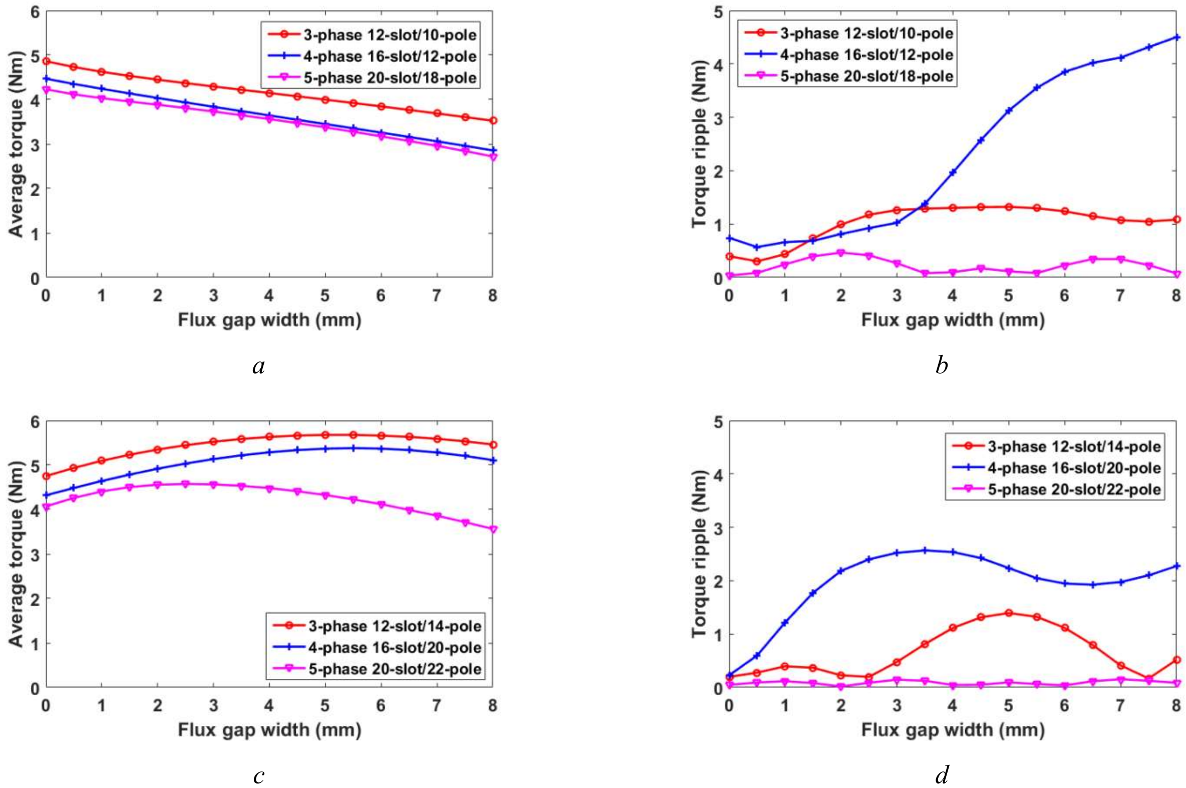


Fig. 8. *Average torque and torque ripple versus flux gap width of modular PM machines with different phase numbers.*
a-b $N_s > 2p$
c-d $N_s < 2p$

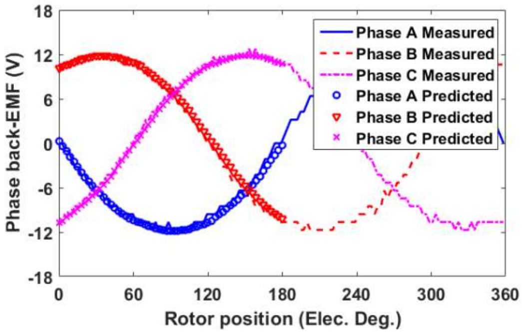
The torque ripples (peak-to-peak torques) follow a similar trend as the peak-to-peak cogging torque. This is mainly due to the fact that higher order harmonics, particularly the 5th and 7th, are quite low in the phase back-EMFs of modular machines and hence the torque ripples due to EMF harmonics are much less dominant than those due to cogging torques.

5. Experimental Validation

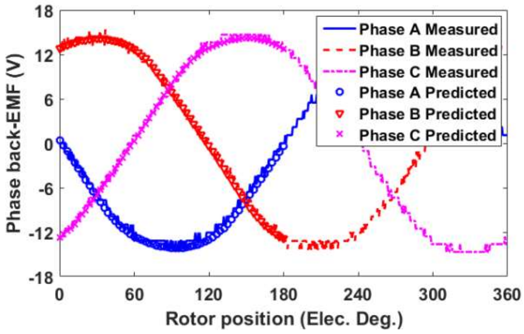
In order to validate the predictions carried out previously, the 3-phase 12-slot/10-pole and 12-slot/14-pole prototype modular PM machines without tooth tips have been built, which are referred to in [24]. The design parameters are given in Table 2 and Table 3.

5.1. Phase Back-EMF

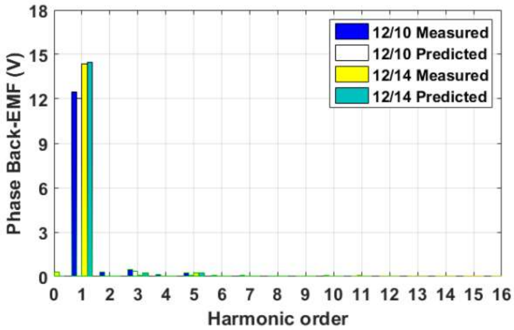
The phase back-EMFs of the prototypes are measured and compared with the corresponding predicted results, as shown in Fig. 9. A good match can be obtained between the predicted and measured results.



a



b

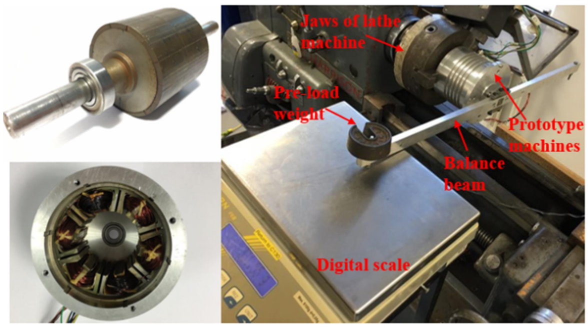


c

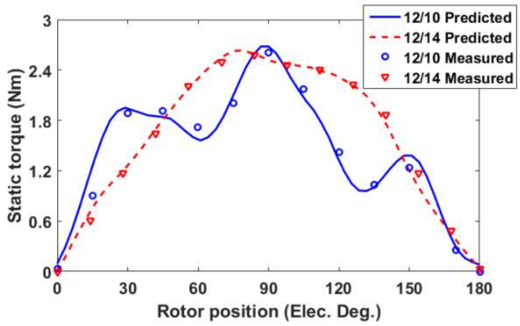
Fig. 9. *Predicted and measured phase back-EMFs.*
a 12-slot/10-pole
b 12-slot/14-pole
c Spectra of phase A as an example

5.2. Static Torque

The static torque against the rotor position can be measured by employing the method presented in [29] and the test rig is shown in Fig. 10 (a). The supply currents to phases A (I_A), B (I_B) and C (I_C) are set as $I_A = -I_B/2 = -I_C/2 = I$, where I is a DC and can be changed to represent different load conditions. It is evident from Fig. 10 (b) that the predicted and measured results are in good agreement for all prototype machines.



a



b

Fig. 10. *Static torque measurement (I=5A).*
a The prototype machines and the test rig
b Static torque versus rotor position

6. Conclusion

Multi-phase modular PM machines with single-layer concentrated windings were investigated in this paper. The optimal slot/pole number combinations for modular PM machines with different phase numbers were identified. The electromagnetic performance such as winding factors, air-gap MMF, back-EMF, cogging torque, average torque and torque ripple have been investigated, it demonstrated that:

- The main sub-harmonics of air-gap MMF are significantly reduced by employing the modular topologies for multi-phase PM machines. This can largely mitigate the negative effects on the electromagnetic performance due to such sub-harmonics.
- For multi-phase modular PM machines having $N_s > 2p$, the FGs have negative effects on the electromagnetic performance such as decreasing the winding factors, MMF working harmonics and average torques, etc.
- For the multi-phase modular PM machines having $N_s < 2p$, if the flux gap width is properly selected, the FGs can improve the electromagnetic performance, such as increasing average torques and reducing the torque ripples.

The predictions obtained by FE have been validated by the experiments. The general rules established in this paper summarized the influence of FGs on the electromagnetic performance of multi-phase modular PM machines. Although only three, four and five-phase cases are discussed, the conclusions achieved in this paper can be extended to modular PM machines with all other phase numbers and can be used as design guidelines for multi-phase modular PM machines in practical applications. Further, although only small size machines have been investigated in this paper for the experimental validation purpose, the established general rules can be extended to the design and analysis of large PM machines, eg. offshore wind generators.

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