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Performance comparison between consequent-pole and inset modular permanent magnet machines

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Abstract: This paper proposes some consequent-pole (CP) modular permanent magnet (PM) machines with different flux gap (FG) widths and slot/pole number combinations. The corresponding inset modular PM machines having the same magnet volume are also presented for comparison. It has been demonstrated that the output torques of the consequent pole modular machines are always higher than those of the inset modular machines regardless of FG widths and slot/pole number combinations. Other electromagnetic performances such as back-EMF, cogging torque, and iron losses etc. are calculated by 2D FEA software and compared as well. The advantages and disadvantages of consequent and inset modular PM machines are summarised here.

1 Introduction

Permanent magnet (PM) machines are employed in a wide range of industrial applications due to their inherent advantages such as high torque density and high efficiency [1]. However, with the ever increasing price and the concern of availability of the PM materials, the optimisation design of the PM machines becomes more and more necessary in order to reduce the overall system cost. The employment of the consequent-pole (CP) topology is an excellent option to meet such a requirement. The rotor of CP topology has only half number of PM poles compared with the conventional surface-mounted PM (SPM) rotor. In addition, all the PM poles share the same polarity which is either N-pole or S-pole and the iron salient poles between the PMs generate the virtual S-pole or N-pole accordingly, as shown in Fig. 1*a*. The major advantage by employing the consequent pole PM machines is significantly reduced amount of PM material [2]

The CP topology can be applied to many types of machines. By way of example, Vernier PM machines [3], partitioned stator flux reversal machines [4], and hybrid excited machines [5] etc. In addition, since the rotor with PMs in CP topology can provide higher radial retaining force as well as the capability of regulating the radial rotor position independently, it is also very suitable for the bearingless PM motor [6–10].

The performance of the CP and conventional interior PM (IPM) machines for electrical vehicle is compared in [11], and it is found that the CP IPM machines have both larger torque density at rated condition and lower cogging torque and torque ripple. Moreover, a larger speed range can be achieved due to better flux weakening capability. However, the conventional IPM machines have better overload capability. In [12], the optimisation and comparison between 44-pole/48-slot fractional-slot concentrated winding PM machines having SPM rotor and CP rotor have been carried out. It reveals that under rated condition, the machines with the SPM and CP rotors have similar performance but the CP rotor consumes 33% less PM material.

The aforementioned machines are all non-modular ones. By employing the modular topology (segmented stator and/or rotor), the consumption of steel lamination materials can be reduced further and the manufacturing process especially the winding process can be eased. Moreover, the modular topology can provide mechanical, thermal, and magnetic separations between the armature windings, and hence the fault tolerant capability can be improved and the on-site maintenance can be minimised [13].

E. Spooner *et al.* in [14–16] have introduced some modular PM generators for wind power applications which have not only modular stators but also modular rotors. The proposed modular machines have slightly higher efficiency but lower active mass compared with the non-modular machines with the same dimensions. Several other new modular stator designs by applying flux barriers (or flux gaps here) for IPM machines are presented in [17–19]. Such modular stator structures can help to effectively reduce the lower order space harmonics and their associated core losses.

The novel modular SPM machines by inserting flux gaps (FGs) into alternate stator teeth are introduced in [13]. The influence of FGs on the electromagnetic performances has been comprehensively investigated. It shows that the FGs exert positive effects on the modular PM machines with slot number (N_S) lower than pole number ($2p$) while for slot number higher than pole number, the FGs degrade the machine electromagnetic performances.

Hence, here, in order to combine the advantages of both the CP machines and the modular topologies, novel CP and inset modular PM machines are introduced, as shown in Fig. 1. The electromagnetic performances such as back-EMF, cogging torque, on-load torque, iron losses etc. for different slot/pole number combinations are investigated and compared.

2 Design of CP modular PM machines

The cross-sections of the CP and inset modular PM machines investigated here are depicted in Fig. 1. In order to avoid heavy
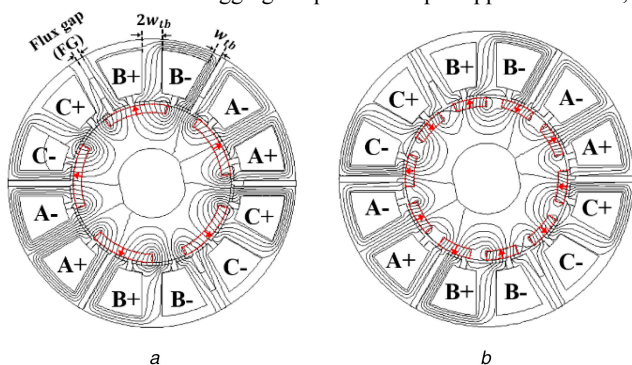

Fig. 1 *Cross-sections of the 12-slot/10-pole modular PM machines with open- circuit flux line distributions*
(a) CP modular PM machine, *(b)* Inset modular PM machine

Table 1 Main parameters of the modular PM machines

tooth body width, mm	7.1	rated current, A_{RMS}	7.34
rated speed, rpm	400	stack length, mm	50
stator outer radius, mm	50	rotor outer radius, mm	27.5
stator inner radius, mm	28.5	magnet thickness, mm	3
stator yoke height, mm	3.7	magnet remanence, T	1.2
filling factor k	0.37	number of turns per phase	132
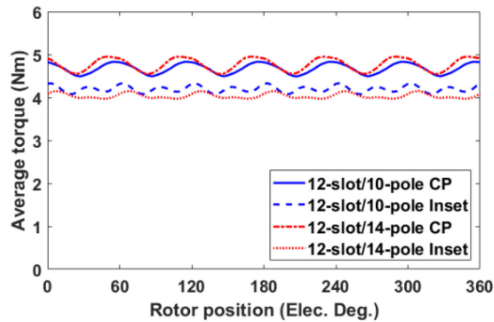
Fig. 2 *Output torque comparison of the CP and inset non-modular PM machines with 12-slot/10-pole and 12-slot/14-pole*

Fig. 3 *Spectra of the phase back-EMFs of the CP and Inset modular PM machines*
(a) 12-slot/10-pole, *(b)* 12-slot/14-pole

Fig. 4 *Cogging torques of the 12-slot/10-pole CP and inset modular PM machines*

local saturation when the FGs are introduced, the total active tooth body width of the stator teeth with or without FGs are kept the same regardless of FG width variation, as shown in Fig. 1*a*. To simplify the investigation, several other general design parameters for CP and inset modular PM machines with different slot/pole number combinations are exactly the same, as listed in Table 1.

The rotor PM pole-arcs of the 12-slot/10-pole and 12-slot/14-pole CP PM machines with conventional stator (non-modular) are optimised individually at rated current in the first place. The modular counterparts will then be developed based on these optimised non-modular ones. It is found that the optimal rotor PM pole-arc of the 12-slot/10-pole CP non-modular PM machine is 47.2 Mech. Deg., while for the 12-slot/14-pole one, the optimal PM pole-arc is 34.5 Mech. Deg.
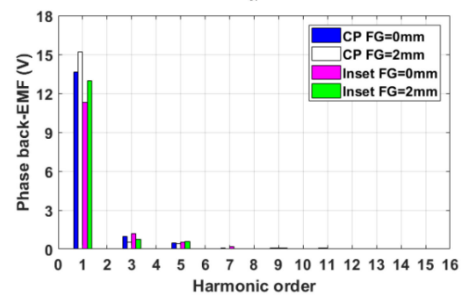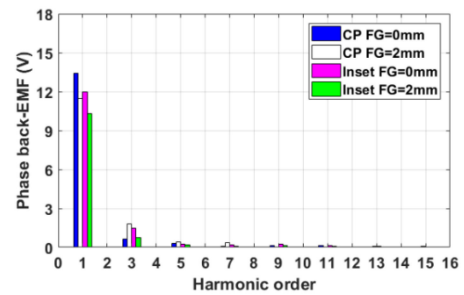
As aforementioned, the inset PM machines and the CP PM machines investigated here have the same volume of PM material, and hence, the PM pole-arcs of the inset modular PM machines with different slot/pole number combinations can be determined according to the optimal PM pole-arcs of the CP PM machines. As a result, the PM pole-arcs for the inset PM machines having 12-slot/10-pole and 12-slot/14-pole are 23.6 and 17.3 Mech. Deg., respectively.

Fig. 2 depicts the output torques of the conventional CP and inset PM machines with the optimal pole-arcs determined previously. It is evident that the output torques of the CP conventional PM machines are higher than those of the conventional inset PM machines. To be specific, for the cases of 12-slot/10-pole machines, the average torque increases by 11.9% from 4.2 to 4.7 Nm. However, for the 12-slot/14-pole ones, the average torque increases by 20% from 4.0 to 4.8 Nm. To conclude, regarding the torque capability, the PM machines having CP topology are better options compared with the inset PM topology if their total PM volumes are the same.
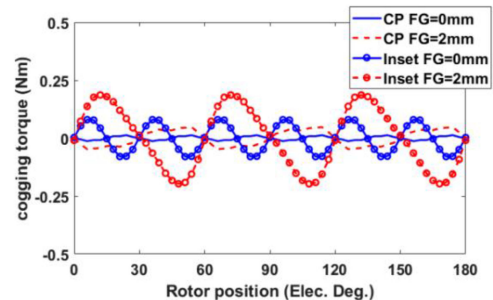
3 Electromagnetic performance of CP and inset modular PM machines

3.1 Phase back-EMF

The phase back-EMFs of the CP and inset modular PM machines are calculated under the rated speed (400 rpm) and their spectra are shown in Fig. 3. It is evident that the CP modular PM machines have higher back-EMFs than the inset modular PM machines regardless of the slot/pole number combinations. This is mainly due to the fact that the flux leakage between the adjacent PM poles of the CP modular PM machines is smaller compared with that of inset PM machines, as can be observed in Fig. 1. In terms of the 3rd harmonics, it is worth noting that for the inset PM machines,

the FGs always reduce their 3rd harmonic component. However, for the CP PM machines, if $N_S > 2p$, the 3rd harmonic back-EMF increases with the increasing FG width, while opposite phenomenon can be observed for $N_S < 2p$.

3.2 Cogging torque

Cogging torque is due to the interaction between the PMs and the stator slot-openings. As have been well established that the periodicity and the magnitude of cogging torque of PM machines is mainly determined by the least common multiple (LCM) between N_S and $2p$ [20] while for modular PM machines, it is determined by the LCM between N_{FG} and $2p$, where N_{FG} is the number of FGs in the stator [21]. As a result, there are 12 cogging torque periods for the conventional non-modular PM machines within one electrical period but half cogging torque periods for their modular counterparts when the value of N_S is 12 and the value of $2p$ are 10 or 14, as shown in Fig. 4.

Fig. 5 shows the peak-to-peak cogging torques of the CP and inset modular PM machines against the FG widths. It is worth noting that the peak-to-peak cogging torques of the CP modular PM machines become smaller than those of the inset modular PM machines regardless of the slot/pole number combinations when the modular PM machines have relatively large FG (e.g. >2.5 mm). Such advantages of employing the CP topology can result in smaller torque ripple compared with the inset modular PM machines as shown in Fig. 6.
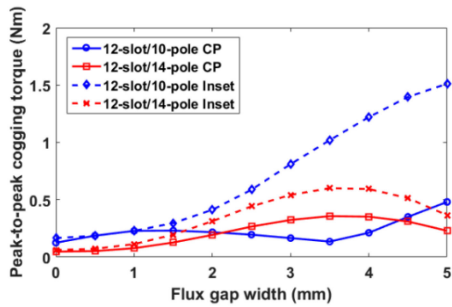
Fig. 5 *Peak-to-peak cogging torques of the CP and inset modular PM machines versus FG widths*
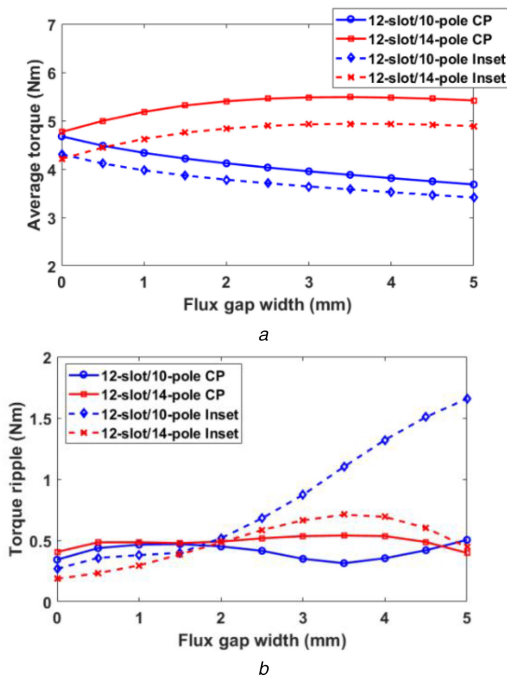

a

b

Fig. 6 *Electromagnetic torque characteristics of the CP and inset modular PM machines*
(a) Average torque, *(b)* Torque ripple

3.3 Electromagnetic torque

The average torques against different current phase angles of the CP and inset modular PM machines with 2 mm FG width are shown in Fig. 7. It can be found that the optimal current phase angle of the CP and inset modular PM machines is 90 Elec. Deg. and is almost not affected by the presence of FGs, as shown in Fig. 7. This means that the reluctance torques of both machine topologies due to the rotor iron salient poles are very tiny and can be neglected.

The average torques and torque ripple (peak-to-peak torque) of the CP and inset modular PM machines with different slot/pole number combinations under the rated three-phase sinewave currents are calculated and illustrated in Fig. 6. It is evident that the average torques can be improved by selecting appropriate FG width for both the CP and inset modular PM machines with $N_S < 2p$. Nevertheless, for the CP and inset modular PM machines with $N_S > 2p$, the average torques are decreased with the increasing FG widths. Such influences of FGs on the average torques come mainly from the influence of FGs on the back-EMFs, especially on the fundamentals, as studied in previous sections. Furthermore, the torque ripple of the CP modular PM machines will be smaller than that of the inset modular PM machines when the FG width is bigger than 2.5 mm, as shown in Fig. 6*b*. It is worth noting that only the torque ripple of the CP modular PM machine can be mitigated slightly by properly choosing the FG width. No torque ripple mitigation can be achieved for the inset modular PM machines unless very large FG width is employed,
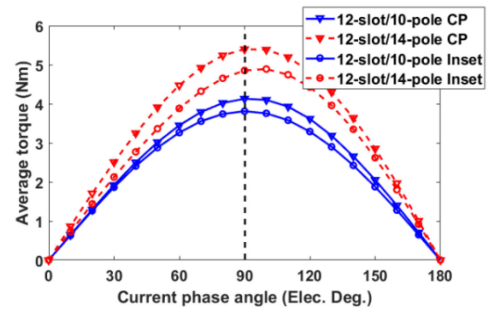

Fig. 7 *Average torques versus current phase angle of the CP and inset modular PM machines with different slot/pole number combinations. (FG = 2 mm)*
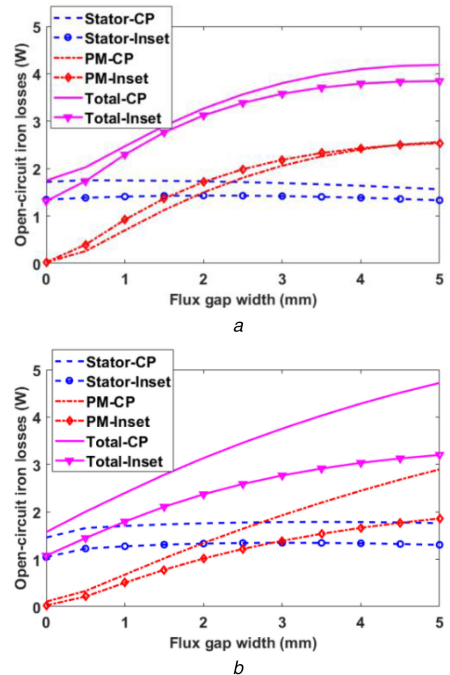

a

b

Fig. 8 *Open-circuit iron losses of CP and inset modular PM machines versus different FG widths*
(a) 12-slot/10-pole, *(b)* 12-slot/14-pole

which makes the winding nearly unfeasible due to very small slot area.

3.4 Iron losses

As the FGs are placed in the middle of the alternate stator teeth of the modular machines, the main magnetic circuit and the air-gap permeance are modified accordingly. As a result, the electromagnetic performances are influenced. However, not only the performances discussed above but also the PM eddy current loss and the iron core losses of the modular PM machines are under the influence of the FGs.

The on-load and open-circuit hysteresis and eddy-current losses under different working conditions in the stator and rotor as well as the PM eddy-current losses of the CP and inset modular PM machines are calculated by 2D FE model. Here, the employed iron losses calculation method is similar to the method presented in [22]. By summing up the iron losses in every mesh element, the resultant iron losses can be obtained. It is worth noting that the iron losses in the laminated rotor core can be neglected due to the fact that the rotor core iron losses are very small compared with the stator iron losses. Therefore, the rotor iron losses will not be shown here. The open-circuit and on-load iron losses of the CP and inset modular PM machines against various FG widths with different slot/pole number combinations are calculated and compared in Figs. 8 and 9, respectively. In order to analyse the influence of the FGs on the iron losses, the air-gap flux densities due to PMs only
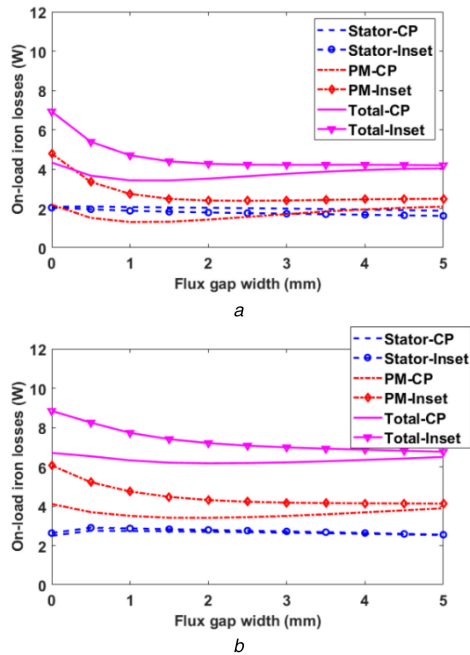
Fig. 9 *On-load iron losses of CP and inset modular PM machines versus different FG widths*
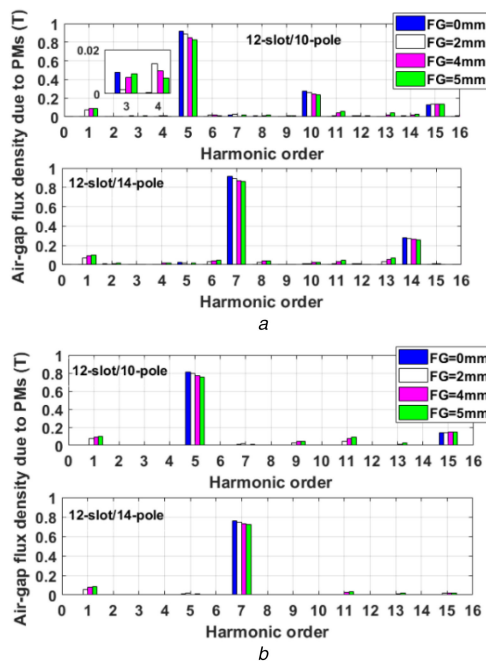*(a)* 12-slot/10-pole, *(b)* 12-slot/14-pole

Fig. 10 *Spectra of open-circuit air-gap flux density versus FG widths*
(a) CP modular PM machines, *(b)* Inset modular PM machines

and armature field only, respectively, are introduced, as shown in Figs. 10 and 11.

3.4.1 Open-circuit iron losses:
The open-circuit iron losses of the 12-slot/10-pole and 12-slot/14-pole CP and inset modular PM machines against different FG widths are illustrated in Fig. 8. It is found that the CP modular PM machines have bigger stator iron losses compared with the inset PM machines regardless of the slot/pole number combinations and FG widths. In order to analyse the reason of such phenomenon, the calculation of air-gap flux density due to PMs only has been carried out and shown in Fig. 10. It is found that not only the fundamentals also known as working harmonics of the CP PM machine, e.g. the 5th order harmonic for the 12-slot/10-pole and the 7th order harmonic for the 12-slot/14-pole, are higher than those of the inset PM machines, respectively, the other harmonic components particularly the higher order

harmonics are also higher. This contributes to higher open-circuit stator iron losses in the CP PM machines. For different FG widths, the stator iron losses of both the CP and inset PM machines are almost unchanged. This is mainly due to the fact that although the fundamental and higher order harmonics reduce the sub-harmonic such as the 1st harmonic increases significantly, compensating the loss reduction due to the reduced higher order harmonics.

The influences of FGs on the open-circuit PM eddy-current losses for both the CP and inset modular PM machines are also depicted in Fig. 8. It has been mentioned previously that the working harmonics of air-gap flux density due to PMs only are the main reason of the stator iron losses, but for the rest harmonic contents, they will cause the PM eddy-current losses. Taking the 12-slot/10-pole CP modular PM machines as an example, it is evident from Fig. 10a that except the working harmonic and the 10th order harmonic, the rest harmonics especially the 1st, 9th, 11th, and 15th order harmonics are increased with the increase in FG width. Therefore, the open-circuit PM eddy-current losses increase with the increase in FG width, as shown in Fig. 8a.

Moreover, it is found that the PM eddy-current losses of the CP modular PM machines with $N_S > 2p$ are lower than those of the inset modular PM machines when the FG width is equal or smaller than 4 mm, while when the FG width becomes bigger than 4 mm, the PM eddy-current losses of CP modular PM machines become slightly larger, as shown in Fig. 8a. The main reason of such phenomenon is that the 1st order harmonics of the air-gap flux density due to PMs only of the CP modular PM machines with $N_S > 2p$ are always lower than those of the inset modular PM machines. Second, the 3rd and 4th order harmonics of the CP modular PM machines are more significant compared with those of the inset modular PM machines, as highlighted in Fig. 10a. By considering those two factors together, the phenomenon observed from Fig. 8a can be explained.

However, when $N_S < 2p$, the CP modular PM machines always have higher PM eddy-current losses than the inset modular PM machines since the CP modular PM machines have higher 1st, as well as 4th, 5th, and 6th order harmonics than the inset modular PM machines regardless of the FG widths, as shown in Fig. 10b.

To conclude, due to the higher stator iron losses, the total open-circuit iron losses of the CP modular PM machines are higher than those of the inset modular PM machines regardless of the FG widths and slot/pole number combinations.

3.4.2 On-load iron losses:
Fig. 9 shows the on-load iron losses of the CP and inset modular PM machines. In order to analyse the influence of FGs on the on-load iron losses, the spectra of the air-gap flux density due to armature field only of the CP and inset modular PM machines with different FG widths are introduced, as shown in Fig. 11. It is worth noting that the CP topology introduces even order harmonics into the air-gap flux density due to armature field only. This is mainly due to the asymmetric rotor structure of CP machines that results in asymmetric air-gap permeance.

It is found from Fig. 9 that the on-load PM eddy-current losses of the CP modular PM machines are always lower than those of the inset modular PM machines regardless of the FG widths and the slot/pole number combinations. This is mainly due to the fact that the 1st order harmonics of CP modular PM machines versus FG widths are always lower than those of inset modular PM machines, as can be seen from Fig. 11, and the 1st order harmonic is the most dominant harmonic for PM eddy current losses.

Additionally, by choosing a proper FG width, the on-load PM eddy-current losses can be mitigated. By way of example, for the 12-slot/10-pole CP modular PM machines, the sub-harmonics, e.g. 1st, 2nd, 4th and the higher order harmonics, e.g. 7th, 10th, 12th are the main sources of PM eddy-current losses. As mentioned above, the 1st order harmonic plays a dominant role on the PM eddy-current losses, and it can be clearly seen from Fig. 11a that the 1st order harmonics can be reduced significantly when the modular topology is introduced and decreases with the increasing FG width, so do the 2nd, 4th, and 10th order harmonics. However, the 7th and 12th order harmonics are increased simultaneously. In addition, the 7th order harmonic is increased until FG width is 4 mm and decreased afterwards. Therefore, by considering all the
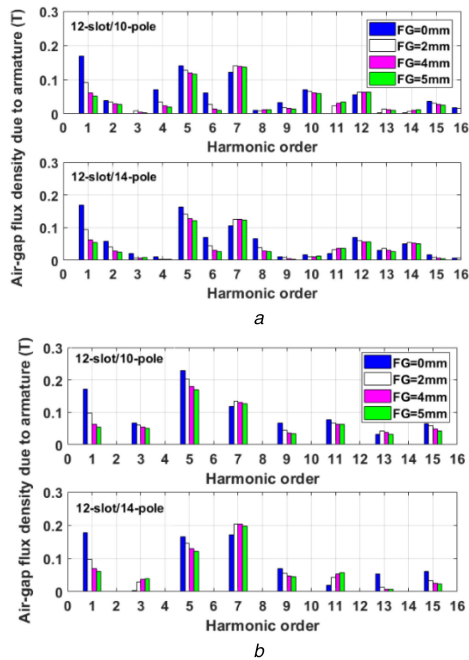
Fig. 11 *Spectra of air-gap flux density due to armature field only versus FG widths*
(a) CP modular PM machines, *(b)* Inset modular PM machines

Table 2 On-load losses of CP and inset non-modular and modular PM machines

iron losses, W	12/10 (non-modular)	12/10 (modular)	12/14 (non-modular)	12/14 (modular)
CP	4.33	3.42(−21.1%) FG = 1.5 mm	6.71	6.18 (-7.9%) FG = 2 mm
inset	6.92	4.19(−39.5%) FG = 5 mm	8.85	6.77 (-23.5%) FG = 5 mm

influences from the 1st, 2nd, 4th, 7th, 10th, and 12th order harmonics, the PM eddy-current losses decrease with the increasing FG width first and then start increasing slightly, as shown in Fig. 9*a*.

Therefore, for both the CP and inset modular PM machines, the on-load PM eddy-current losses can be reduced by choosing an appropriate FG width. As of the influence of FGs on the on-load stator iron losses is very limited, thus, the total iron losses can also be reduced by properly choosing the FG widths of all the modular PM machines investigated here.

4 Conclusion

Here, the CP and inset modular PM machines have been proposed and compared. Several advantages of CP modular PM machines over the inset modular PM machines have been found:

- With the same amount of PM material, the average torques generated by the CP modular PM machines are higher and the torque ripples can be lower. In addition, the torque ripples of CP modular PM machines can be mitigated slightly by relatively wide FGs.
- The CP modular PM machines have smaller on-load losses. In addition, the on-load losses of both machines can be reduced by employing appropriate FG widths, as listed in Table 2.

However, the drawbacks of CP modular PM machines still cannot be overlooked, e.g. under the open-circuit condition, the losses of CP modular PM machines are always higher than those of the inset modular PM machines regardless of the FG widths and the slot/pole number combinations. The influences of FGs on the open-circuit PM eddy-current losses of both machine topologies are negative, so do the total open-circuit iron losses.

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