Modularity Techniques in High Performance Permanent Magnet Machines and Applications

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(Invited)

***Abstract*—This paper reviews the modularity techniques in the stator manufacture of permanent magnet machines for different applications. Some basic concepts of modular machines are firstly introduced. Modular machines for several typical applications are then described in details, including domestic appliances, automobiles and electric vehicles, more electric aircrafts and civic applications, wind power generators, etc. Besides, the influence of manufacture tolerance gaps and flux barriers on the electromagnetic performance is discussed.**

***Index Terms*—Domestic appliance, electric vehicle (EV), modular machine, more electric aircraft, permanent magnet, wind power generator.**

I. Introduction

THE applications of permanent magnets (PMs) to electrical machines can be dated back to the 19th century when there were only low energy density PM materials being used [1], for example magnetite (Fe_3O_4). With the development of PM materials over the past century, i.e. AlNiCo [2-4], ferrite [5], SmCo and NdFeB [6-8], the corresponding PM machines have been fast developing in recent decades as well. The use of PM machines mainly has following advantages [9]:

(1) PM brushless machines have simple structure and the reliability will be much higher compared with those electrical machines having brushes and commutators, such as electrically excited synchronous machines and universal machines.

(2) Since there is no extra field excitation, the excitation loss can be eliminated. Therefore, the efficiency will be high.

(3) Because of the adoption of high energy density PMs, the electrical machines can be made in smaller size if the same torque are to be achieved, compared with the conventional electrical machines without PMs. This means PM machines have higher torque density. Furthermore, the smaller rotor will improve the dynamic performance of electrical machines as well.

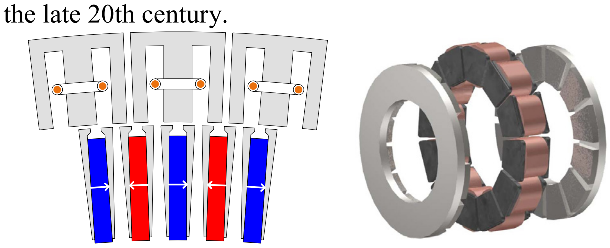
(4) High power factor can be obtained, which reduces the required converter capacity and reduces the total cost of the whole electrical machine drive system.

Since the demand of PM machines is increasingly high, the manufacture technology accordingly becomes more and more concerned. Modularity techniques are correspondingly developed to improve the production efficiency. This technique has been widely used in large hydroelectric alternators for a long time [10]. With the evolution of PM machine technology, quite a few electrical machine topologies have been put forward over the past few decades [11-19]. The modularity techniques are further extensively developed and have been employed to the stator manufacture of these electrical machines.

This paper reviews alternate modular machine topologies for different applications. Some basic concepts of modular machines are firstly introduced. Modular machines for several typical applications are then individually reviewed, e.g. domestic appliances, automobiles and electric vehicles, more electric aircrafts and civic applications, and wind power generators etc. Finally, the influence of manufacture tolerance gaps and flux barriers on the electromagnetic performance is discussed.

II. Basic Concepts of Modular Machines

Fig. 1 shows two examples of modular machines proposed in the late 20th century.



(a) (b)

Fig. 1. Illustration of modular machines. (a) E-core modular stator and modular IPM machine [20]-[23]. (b) Modular stator YASA axial flux machine [24]

Fig. 1(a) shows a wind power generator stator with E-core segments [20] and it was systematically analyzed in [21-23]. Both stator and rotor cores are segmented to make a fully modular machine. Since there are large slot and pole numbers, the mechanical support of this electrical machine is complicated. This constrains the use of such structure in real applications. Besides, too much stator space has been wasted and the output torque will be reduced compared with the conventional non-modular machines. For the modular machine shown in Fig. 1(b), it is yokeless and segmented armature (YASA) axial flux type [24]. The stator iron of this machine has been largely reduced and the torque density is consequently improved. However, the axial field machine has a complicated structure and need much stronger support to keep the

This article was submitted for review on 27, February, 2018.

This work is partially supported by Midea Welling Shanghai Research Centre, Sheffield Siemens Wind Power Research Centre, UK, and the Royal Academy of Engineering/Siemens Research Chair Program, UK.

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mechanical air-gap between stators and rotors, which could cause high production cost.

As mentioned above, the complex structures of these two kind modular machines impede their further promotion. For the real applications, the stators of radial flux PM machines can be easily segmented if non-overlapping winding is used. An example of modular stator construction is shown in Fig. 2 [25-28]. The stator consists of segmented single tooth shown in Fig. 2(a). In order to ease the assembly process, the stator yoke is cut into special shape with connection joints. Fig. 2(b) shows that the complete stator is obtained by connecting all of the segments together.

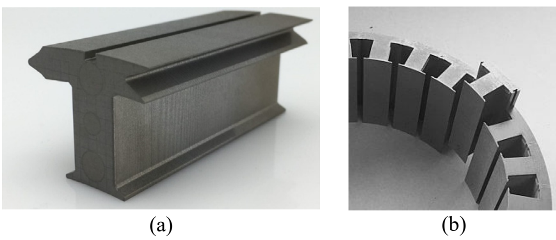


Fig. 2. Modular fractional-slot machines. (a) One segment [25]. (b) Integration of the stator [26].

The shape of joint connections between segments is an important issue for the mechanical integration of these modular machines. Several options are shown in Fig. 3 [29]-[31]. Fig. 3(a) shows some ideal joint shapes, which can tightly fix segments within the stators. Nevertheless, the unavoidable manufacture tolerance will increase the requirement of manufacture accuracy. On the contrary, the simple joints shown in Fig. 3(b) are more preferable in practice. Since each segment can be assembled by joint connections with flexible simple shape in stator yoke, the whole stator will be easily constructed and fixed tightly within a stator frame, and thus the production efficiency is quite high and the manufacture requirement is not as high as those joints with complex shape.

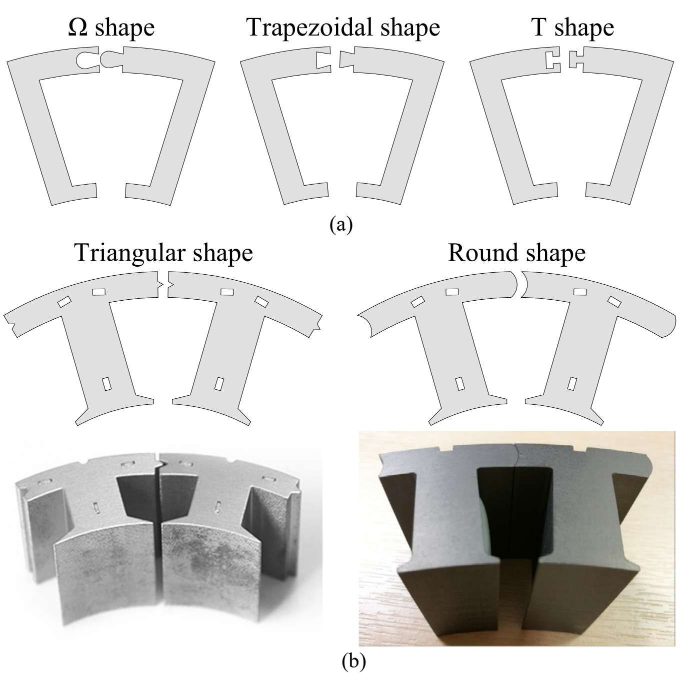


Fig. 3. Mechanical assembly. (a) Ideal [29], [30]. (b) Practical [25], [31].

There are still other challenges for modular machines, for instance, the relative lower reluctance torque in interior PM (IPM) machines with non-overlapping windings. Nevertheless, the advantages of adopting modular stators are obvious as well [32-35]:

(1) The requirement of stator machining will be lower, since only the small portions need to be manufactured instead of the whole stator. Therefore, the production efficiency is high.

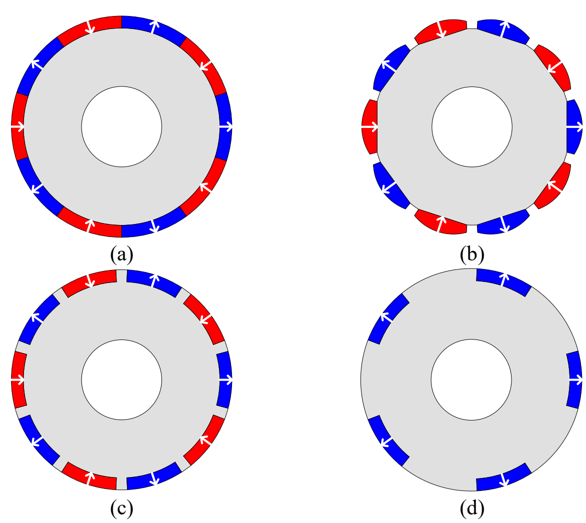
(2) Modular stator is beneficial to winding automation. The windings are easier to be accommodated in the stator slots. Thus, the slot filling factor will increase, which benefits the electrical machine performance.

(3) The transportation of small stator segments will be much easier for large size electrical machines and the cost will be accordingly reduced.

(4) The fault-tolerant capability of electrical machines will be better since the physical, electric, magnetic and thermal isolation among coils could be fulfilled.

In order to easily discuss different modular machines, they are classified into three kinds based on the physical isolation level between adjacent coils. When all teeth wound winding is adopted, the stators can be made of several segments. However, the adjacent coils still touch each other in slots, viz. physical coupling. When the stator windings or cores are specially designed, some parts of adjacent coils will be isolated by stator teeth. This constructs physical partial decoupling modular machines. When any two adjacent coils do not touch each other, there is no physical coupling among coils, which leads to fully physical decoupling modular machines.

Although the modular structures discussed in this paper focus on stators, it is worth noting that a vast number of rotors can be employed. Some available alternate PM rotors are shown in Fig. 4 [9], [36]. It is also worth noting that the rotors may also be made modular, e.g. Figs. 5(a) and (b) showing alternate segmented rotor structures with dovetail interlocks [37], [38], although the mechanical integrity of the complete rotor and the mechanical stress of rotor segments become more critical.



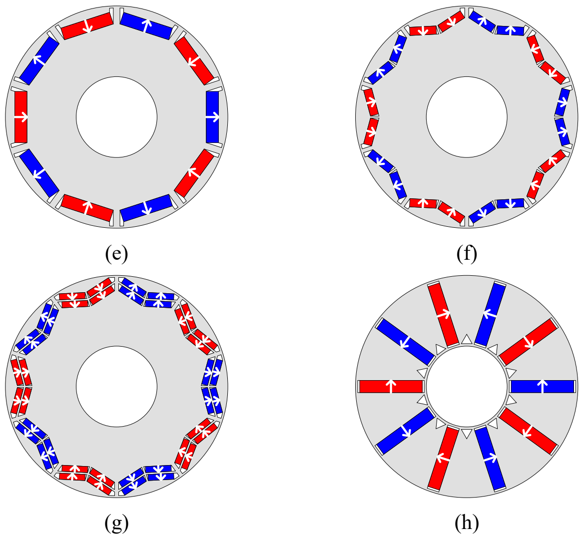


Fig. 4. Alternate rotors. (a) Surface-mounted PM (SPM) rotor. (b) Surface-mounted bread-loaf PM rotor. (c) Surface-inset PM rotor. (d) Surface-inset consequent pole PM rotor. (e) Radially magnetized interior PM rotor with I-shape PMs. (f) Radially magnetized interior PM rotor with single layer V-shape PMs. (g) Radially magnetized interior PM rotor with double layer V-shape PMs. (h) Circumferentially magnetized interior PM rotor.

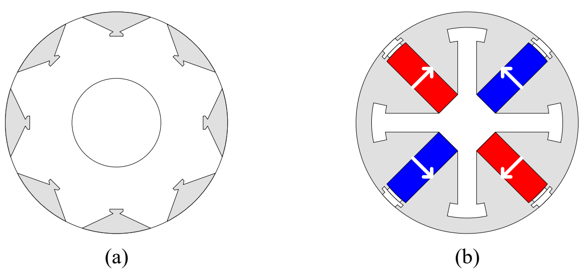


Fig. 5. Alternate modular rotors. (a) Dovetail segmented rotor 1 [37]. (b) Dovetail segmented rotor 2 [38].

III. Domestic Appliances

The main reasons for using modular machines in domestic appliances, such as air-conditioner (compressor) and washing machine, etc., are high manufacturability by automation and manpower cost reduction. A good method in manufacturing the segmented stators can be seen in Fig. 6 [39], [40], where for 9S/6P, "S" stands for slot number and "P" stands for pole number.

The winding process is illustrated in Fig. 6(a) where each stator tooth segment is tightly wound with the help of winding nozzle. Since each time only one coil is wound with very big slot openings, enough space is provided for winding process and the high slot filling factor can be easily achieved. This is beneficial to high manufacture efficiency. The real wound stator segments are shown in Fig. 6(b). Fig. 6(c) shows the complete modular machine product. The surface-inset PM rotor topology with shaped magnets is adopted in this application. When the stator is formed and the coils are compressed in the slots, it can be seen that the wires are closely accommodated in the slots, which illustrates the merit of high slot space utilization. Moreover, compact wire accommodation is also beneficial to the thermal dissipation. Another modular machine with the same slot/pole number combination and different rotor is shown in Fig. 6(d) for further clarity.

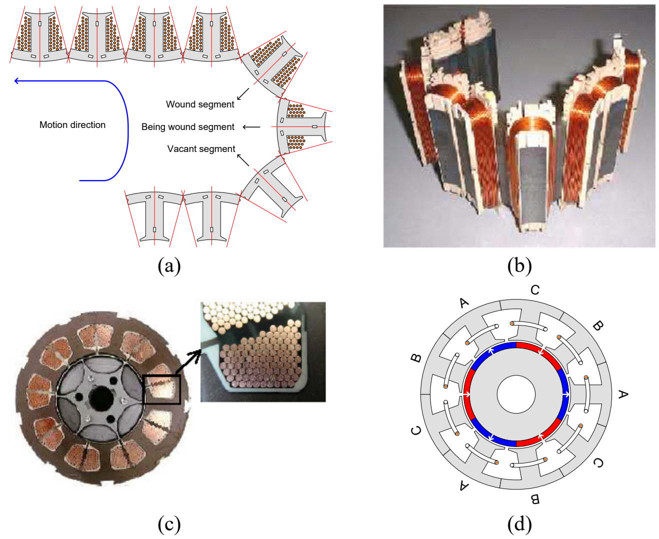


Fig. 6. Mitsubishi compressor (9S/6P) [39], [40]. (a) Winding process. (b) Practical stator segments with coils. (c) Cross-section of the product. (d) Modular machine with SPM rotor.

For the sake of easier stator segment integration, the stator segment should not be fully separated with each other, as shown in Fig. 6(a) and Fig. 7 [41]. Fig. 6(a) shows a very high efficient production method. The complementary interlocked linear machine type laminations can significantly reduce the material cost since only some small portions of laminations are wasted. Due to large slot openings with linear machine type laminations, the winding process will be much easier compared with the conventional machines. Bending the stator yoke and forming the whole stator by connecting two segments together, the production efficiency is obviously high and the winding filling factor is also very high. The final assembled modular machine with small slot openings is illustrated in Fig. 7(b).

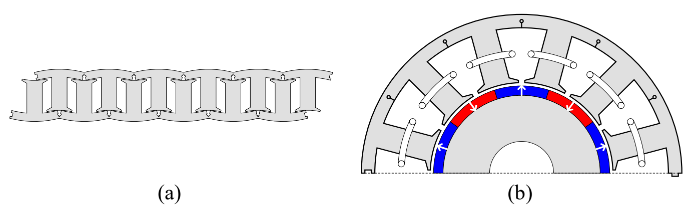


Fig. 7. Midea compressor (12S/10P) [41]. (a) Stator segments for modular machines. (b) Cross-section of the assembled modular machine.

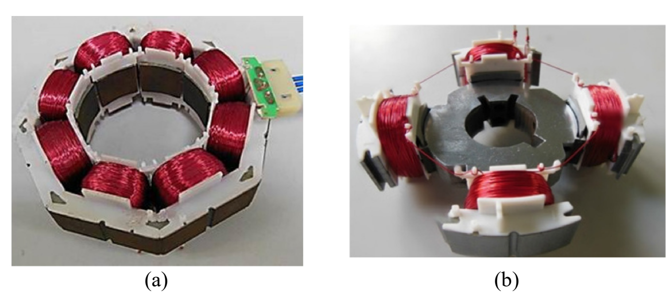


Fig. 8. Midea washing machine stator manufacture process [42]. (a) Complete stator. (b) Half stator.

Fig. 8 [42] shows a stator with 8 coils in total. It can be separated into two identical modular parts, each containing only 4 coils/teeth uniformly distributed in space. Thus, it is very easy to wind the half stator with extremely large airspace between the teeth. After each modular part is wound, the complete stator can be easily assembled from two half stators. It must be emphasized that the examples shown in this section all belong to physical coupling type modular machine.

IV. Automobiles and Electric Vehicles

PM machines are widely used in automobiles, for instance integrated starter/generator, electric vehicle (EV), etc. A few modular machine topologies have been proposed by different companies. Accounting for the advantages of non-overlapping windings, viz. modular stator segment, short end winding, high torque density and low torque ripple [43]-[47], they have been employed in some EVs, as shown in Fig. 9.

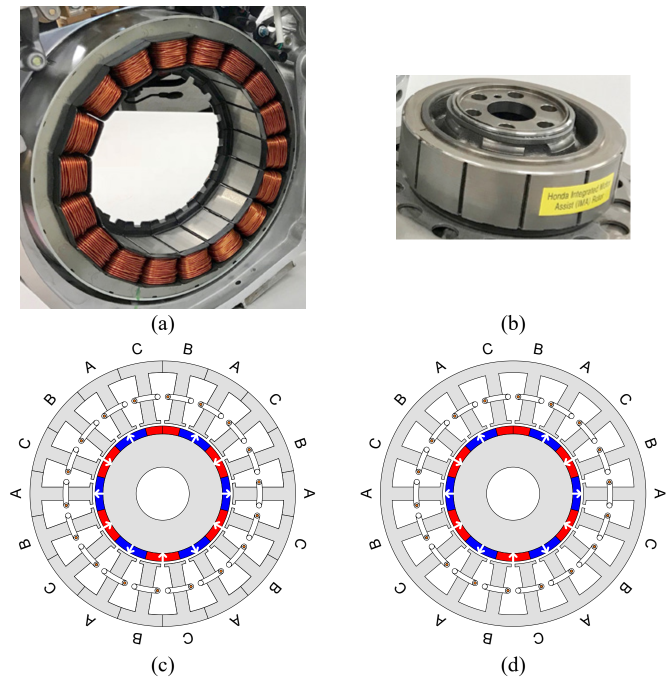


Fig. 9. Non-overlapping windings for EV application with all teeth wound winding (18S/12P). (a) Stator of Honda product [44]. (b) Rotor of Honda product [44]. (c) Cross-section with modular stator. (d) Cross-section with conventional stator.

A product of Honda is shown in Figs. 9(a) and (b) for its stator and rotor, respectively. The rotor PMs are optimized to obtain high output torque and low torque ripple. The cross-section of the assembled machine is shown in Fig. 9(c), together with its counterpart machine with conventional stator shown in Fig. 9(d). However, the modular machines with non-overlapping windings can hardly generate reluctance torque when IPM rotors are used [47].

The commercial Prius 2010 PM machine is well-known for EV application, as shown in Fig. 10 [48]. This 48S/8P PM machine contains four 12S/2P minimal electrical machine repetition units and the single layer fully pitched overlapping winding is adopted. The stator and rotor of the real product are shown in Figs. 10(a) and (b), respectively. Fig. 10 (c) shows its schematic of cross-section. It adopts overlapping winding and the stator cannot be made into modular segments due to such end connections. In contrast, the winding connection shown in Fig. 10(d) can be adopted as well and the arrangement of end parts within one pole pair guarantees the modular stator can be constructed. With such kind of winding layout, this machine belongs to the partial physical decoupling type, while the electromagnetic performance of two cases will be nearly the same. The larger reluctance torque exists in this kind of machine due to high saliency and fully pitched windings, which results in high torque per PM volume. However, the longer end winding will generate higher copper loss and careful design is also necessary to reduce the large torque ripples in integer slot PM machines.

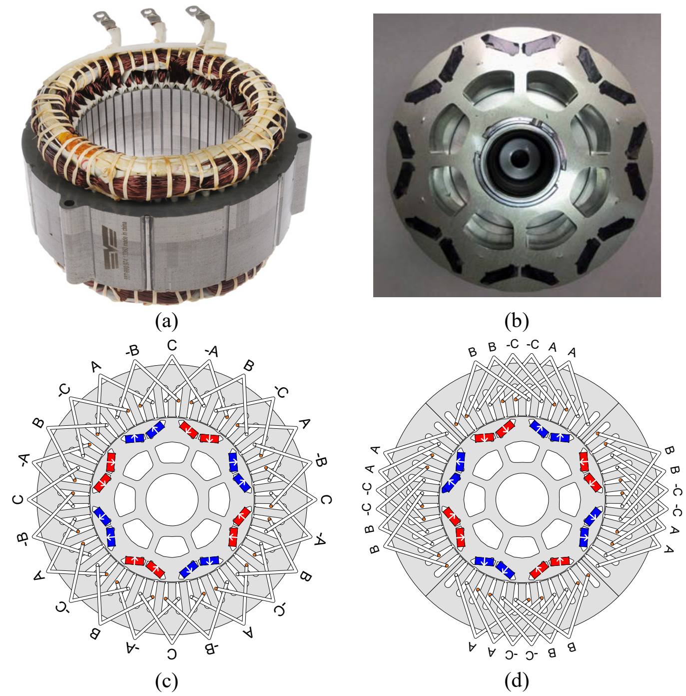


Fig. 10. Prius 2010 PM machine (48S/8P) [48]. (a) Stator. (b) Rotor. (c) Complete non-modular topology. (d) Modular topology.

Another example of modular stator is shown in Fig. 11. The IPM machine with non-overlapping winding is used for power steering [49]. Fig. 11(a) demonstrates that this modular machine has 12S/10P combination and the rotor surface has been shaped to reduce the torque ripple. Since the closed slots are used for the stator, all of the stator teeth construct a complete part and are separated from the stator yoke. Thus, the coils can be wound from the slot bottom with very large openings which are desirable for winding process.

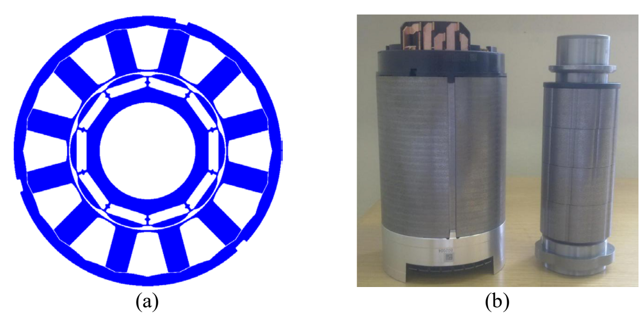


Fig. 11. Segmented 12S/10P stator with separate teeth and yoke [49]. (a) Cross-section. (b) Real products.

V. More Electric Aircrafts and Civic Applications

When PM machines are applied to more electric aircraft, the high reliability and high power density are required [50]. With the increase of aircraft size, megawatt powers should be provided in the future. Due to these reasons, modular PM machines with alternate teeth wound winding are preferable. They are inherently fully physical decoupling and highly fault-tolerant. A 6-phase 12S/8P modular machine is shown in Fig. 12 [32], [51] for aerospace application, together with 3-phase modular machines. It clearly shows that each phase of this modular machine is also electrically, thermally and magnetically isolated from other phases.

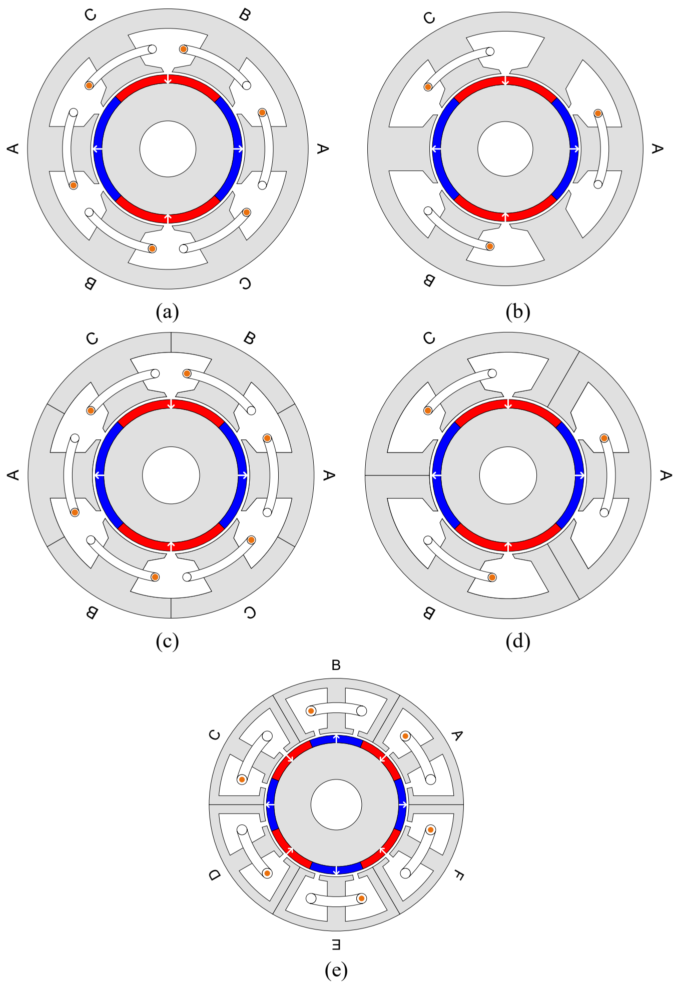
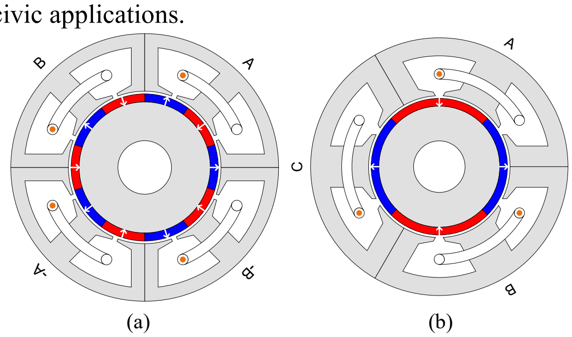


Fig. 12. PM modular machines. (a) Conventional 3-phase all teeth wound. (b) Conventional 3-phase alternate teeth wound. (c) Modular 3-phase all teeth wound. (b) Modular 3-phase alternate teeth wound. (e) Modular 6-phase for aerospace application.

Since the alternate teeth wound winding was proposed, this kind of winding has been investigated for quite a long time [11], [52-59]. Besides 6 phases, it can also be applied to PM machines with other phase numbers [60], [61], as shown in Fig. 13 for 2-, 3-, 4- and 5-phase cases, 3-phase being most popular for civic applications.



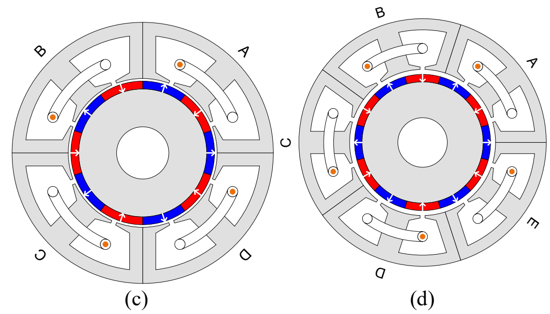


Fig. 13. PM machines with alternate teeth wound windings. (a) 2 phases (8S/10P). (b) 3 phases (6S/4P). (c) 4 phases (8S/10P). (d) 5 phases (10S/12P).

When the alternate teeth wound winding is adopted, the stator tooth width can be accordingly adjusted to increase winding factors [11], [52]. Then, the modular machine has unequal tooth width and the output torque could be higher compared with its equal tooth width counterpart, as shown in Fig. 14. It can be shown that for maximizing the torque, the width of the teeth with coils in 12S/10P unequal teeth PM machines should be wider, while the width of the teeth with coils in 12S/14P unequal teeth PM machines should be narrower. The issue for using unequal tooth width stator is relatively large torque ripple, which is owing to heavier local saturation [62].

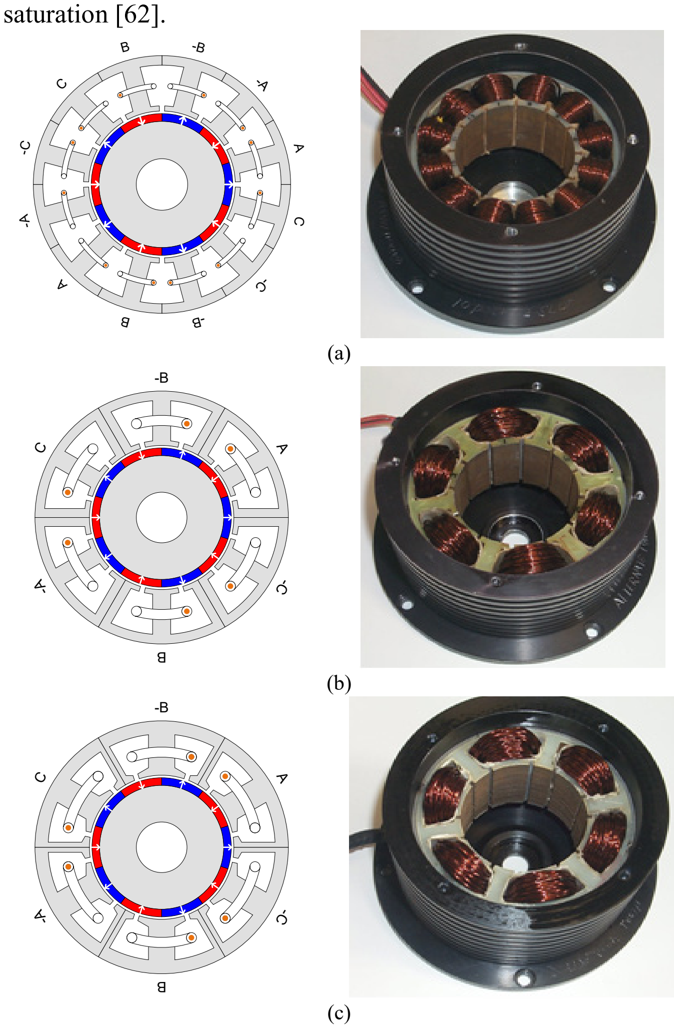
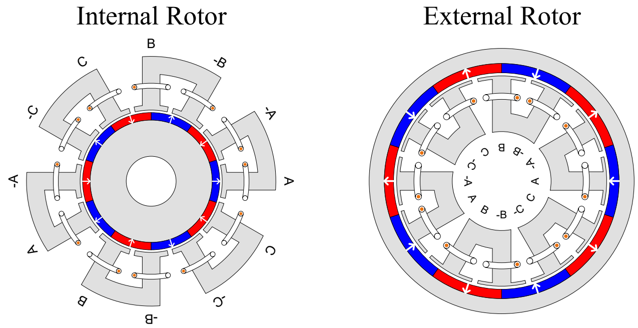
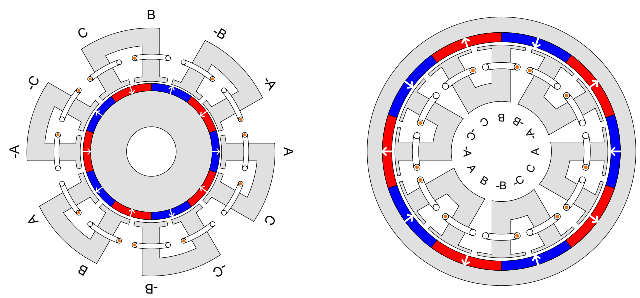


Fig. 14. Modular PM machines with equal and unequal teeth (12S/10P). (a) Equal tooth width stator and all teeth wound. (b) Equal tooth width stator and alternate teeth wound. (c) Unequal tooth width stator and alternate teeth wound.



(a)



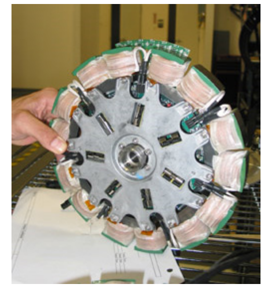
(b)

Fig. 15. Modular machines with flux barriers in different positions (12S/10P). (a) Flux barriers within the different phases (one segment with the same phase). (b) Flux barriers within the same phase (one segment with different phases).

The modular stators in [33], [34], [63], [64] have flux barriers alternately in stator yokes, as shown in Fig. 15. The flux barriers are located between different phases. Thus, each U-core segment contains the coils of the same phase and the whole stator consists of several U-core pieces. The barriers are added within the same phase, viz. each U-core segment containing the coils of different phases, the magnetic circuit of armature field will be changed. The purpose of adopting such structure is to reduce some harmful harmonics [64]. Fig. 15(b) shows its structure. However, there are some disadvantages using this modular method. On one hand, the existence of additional flux barriers in stator yoke will increase magnetic circuit reluctance and the average torque will be reduced. On the other hand, the stator yoke thickness must be increased to the same as tooth width to avoid over saturation. This will lead to a larger volume if an internal rotor structure is adopted, as shown in the left column of Fig. 15. In contrast, this side effect will not exist anymore if the external rotor structure is adopted. The machine topologies in the right column of Fig. 15 can clearly show this, which means this kind of modularity technique can be applied to some special occasions. One application using this kind of modular machine is shown in Fig. 16. Although the advantage of adopting external rotor structure is taken into account, they are really not suitable for electric bicycles. For such low cost application, it is much cheaper to employ conventional fractional slot PM machines.

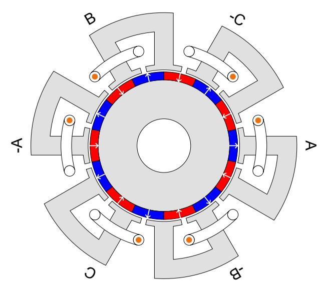
It is worth noting that due to the physical coupling between adjacent coils, these modular machines need some change in order to be available for more electric aircraft application. Since half of the stator teeth are not wound, the stator cores can also have other modular structures. The above mentioned

(a)



(b)

Fig. 16. Application of modular machine with flux barriers in electric bicycle. (a) The wheel with the whole modular machine [65]. (b) Stator of the product [66].



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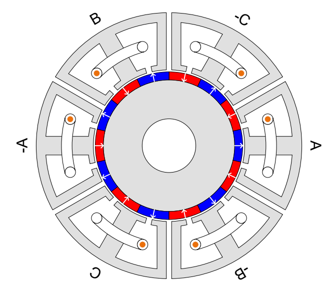

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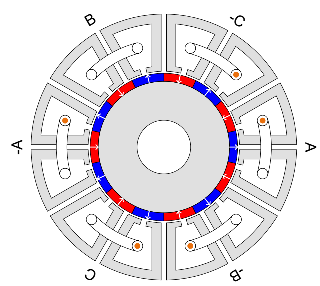

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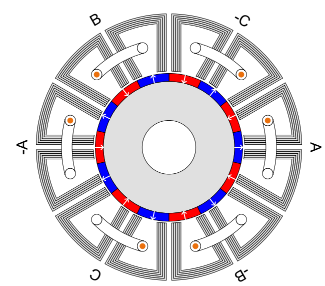


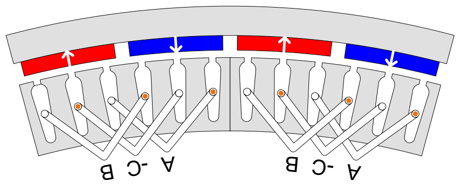
(d)

Fig. 17. Cross-sections of modular machines with flux barriers (12S/14P). (a) U-core stator. (b) Flux barriers in alternate unwound teeth. (c) Flux barriers in all teeth. (d) Axially-laminated core.

U-core stator [34] is shown in Fig. 17(a) for alternate teeth wound winding. The careful protection is needed for this structure because of the exposed coil sides. The additional flux barriers can be inserted into stator teeth, as shown in Fig. 17(b) [18], [67]. When the PM pole number is larger than slot number, such kind of topology can have higher torque compared with its counterpart modular machine without barriers [68]. The U-core stator can also be adopted in this electrical machine [18], as shown in Fig. 17(c) and (d). For the later one, the stator U-core is made from axially-laminated technique.

VI. Wind Power Generators

For PM machines used in wind power generation, the low speed direct-drive type is more pervasively employed for off-shore application. Because of this, the generator size is large and the stator segmentation is necessary for manufacture, transportation, assembly, maintenance, as well as repairing. When integer slot fully pitched single layer winding is adopted, the stators can be automatically separated into segments based on the basic electrical machine unit. An external rotor PM machine was shown in Fig. 18 [69], [70]. Although the stator winding end parts are overlapped among phases within each pole pair, there is no physical coupling between adjacent basic electrical machine units (6S/2P). Therefore, the stator can be cut into a few segments and the coils located at the end part can be protected by stator tooth as well, which is similar to the previous modular machine for EV application.

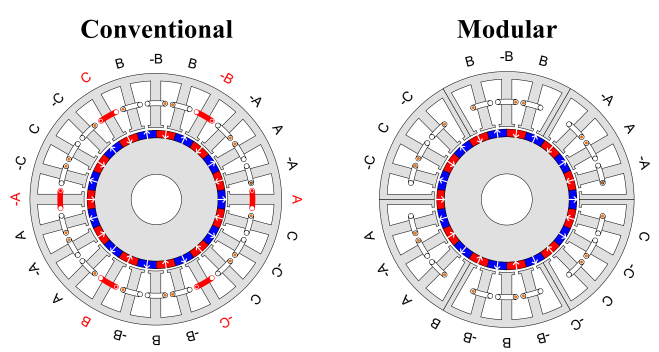


(b)

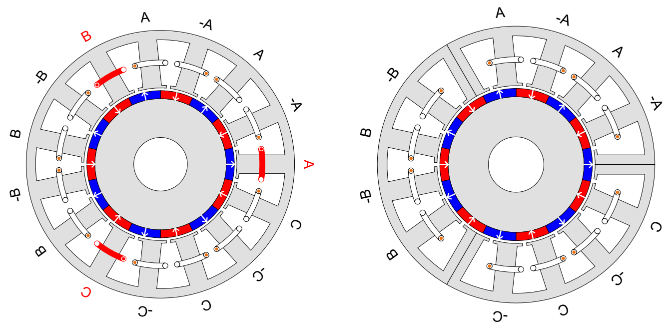
Fig. 18. An external rotor wind power generator (144S/48P).

Apart from overlapping windings, all teeth wound non-overlapping windings can be used in wind power generation as well. It is obvious that the stator segment cannot be protected by tooth body if the conventional all teeth wound winding is used, as shown in the left column of Fig. 19. In [13] some coils of all teeth wound windings are removed to provide the redundant teeth for modularity. The removed coils must be able to construct a balanced 3-phase system to keep the proposed modular machine still balanced. The two PM machines representing slot and pole numbers differed by one and two are shown in Fig. 19. It clearly shows that the more coils need to be removed for 24S/22P PM machine, since it has two complementary winding groups for each phase. However, it only needs to remove 3 coils for 15S/14P PM machine. Abundant harmonics are the major issue for this method.

If some space is left between segments on purpose, the redundant teeth can be arranged in these positions. This method was proposed in [71]. The two modular machines obtained by this method are shown in Fig. 20. Each segment only has coils belonging to one phase and the coil pitch is assigned the same as the pole pitch to obtain unity winding factor. The reason for using the topology in Fig. 20(b) is to get rid of undesirable unbalanced magnetic force, which exists in the PM machine with rotating asymmetric winding layout [72] shown in Fig. 20(a). Larger on-load torque ripple may restrict the promotion of this method.

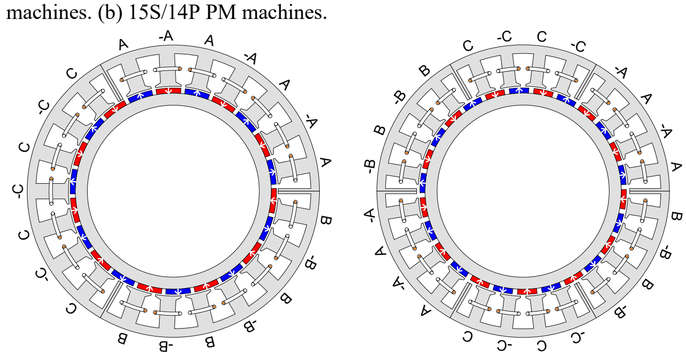


(a)



(b)

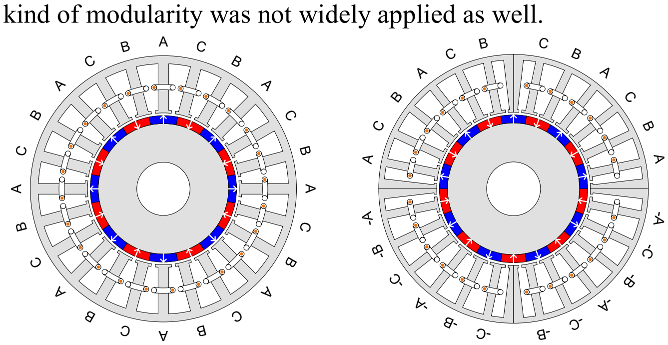
Fig. 19. Modular machines with mixed layering windings. (a) 24S/22P PM machines. (b) 15S/14P PM machines.



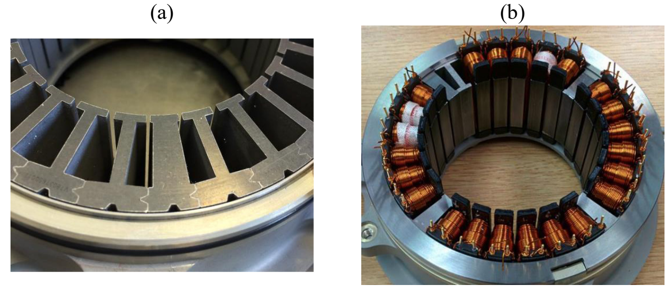
(a) (b)

Fig. 20. Modular machines with redundant teeth. (a) 24S/22P PM machine. (b) 30S/26P PM machine.

The similar method was proposed in [73], where each segment has complete 3-phase winding, as shown in Fig. 21. Fig. 21 shows that the original 18S/12P PM machine has all teeth wound winding. In order to add some redundant teeth to ease modularity, another pole pair is added and used for redundant teeth arrangement. The four redundant teeth are inserted to construct complementary segments. Since three phases are unbalanced and the torque ripple is also large, this kind of modularity was not widely applied as well.



(a) (b)



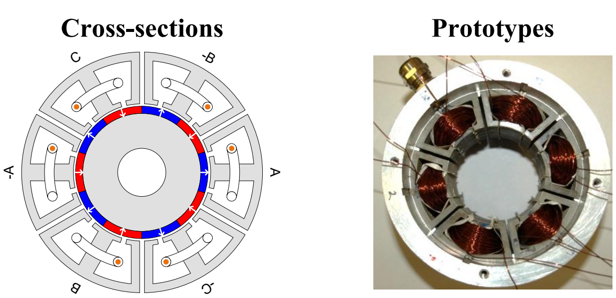
(c) (d)

Fig. 21. Modular machines with complete winding for each segment. (a) 24S/16P PM machine. (b) 28S/18P PM machine. (c) Modular stator core. (d) Complete modular stator.

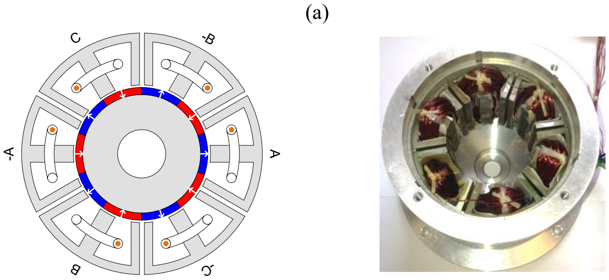
VII. INFLUENCE OF MANUFACTURE TOLERANCE GAPS OR FLUX BARRIERS ON MODULAR MACHINES

From Figs. 15 and 17, it has shown that flux barriers can be introduced in the modular stator machines. Further, for any modular machine, if the stator is made from segments, the manufacture tolerance gaps between segments inherently exist. In [49], it is shown that the cogging torque is particularly sensitive to the manufacture tolerances. In this section, the influence of manufacture tolerance gaps or flux barriers (both are physically the same in terms of airspace gap) on the output torque is investigated. Different tooth-tips can be adopted for such modular machines with flux barriers in unwound teeth, as shown in Figs. 22 and 23 for symmetrical and asymmetric tooth-tips, respectively. Fig. 22(a) shows the similar modular machine as the one in Fig. 17(b), while the difference is the rotor pole number and the corresponding winding arrangement. The influences of flux barrier width on winding factor and average torque are shown in Figs. 22(c) and (d), which verifies the statement above. If there are no tooth-tips in this kind of modular machine, the influence of flux barrier width will have practically the same effect on electromagnetic performance as those counterparts with tooth-tips [74], [75]. Fig. 22(b) shows such an example, whereas the performance will be worse than its counterpart machine shown in Fig. 22(a) owing to the lack of tooth-tip flux focusing effect. In [76], it identifies that the tooth-tips should be arranged in unwound teeth if the slot number is lower than pole number and vice versa for the modular machines having higher slot number than the pole number. Figs. 23(a) and (b) are representatives for these two kinds of asymmetric tooth-tips, respectively. The variation of winding factors for two modular machines with different asymmetric tooth-tips and slot/pole number combinations are shown in Figs. 23(c) and (d).

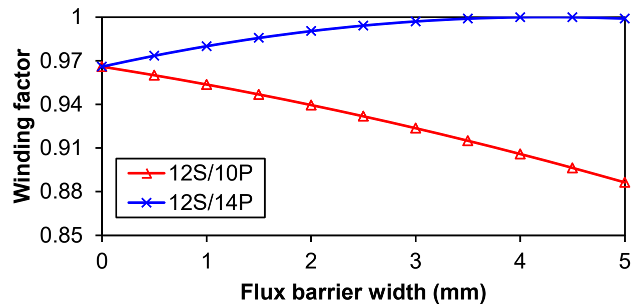
Overall, the influence of flux barrier width and tooth-tip width on pitch factor plays the dominant role [68], [74-76].



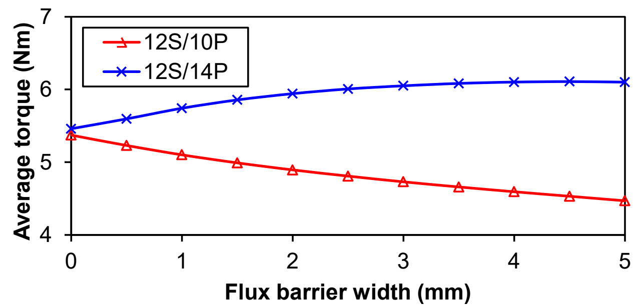
(a)



(b)

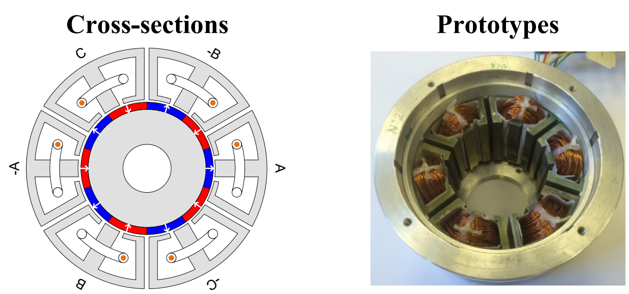


(c)

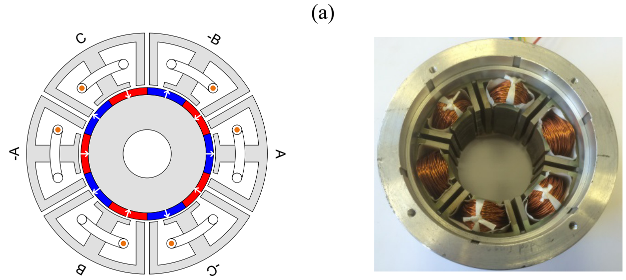


(d)

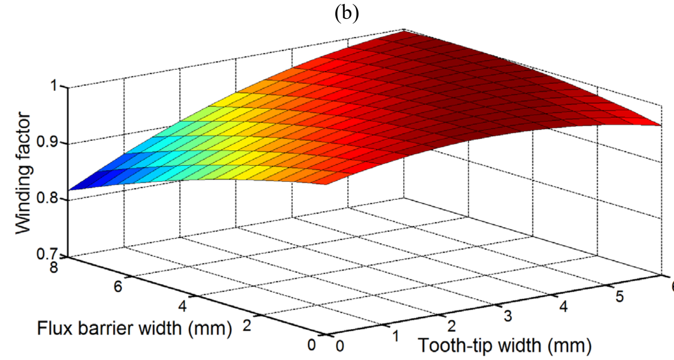
Fig. 22. Cross-sections of modular machines with flux barriers in unwound teeth (12S/10P). (a) Symmetrical tooth-tips. (b) Without tooth-tips. (c) Influence of flux barrier width on winding factor. (d) Influence of flux barrier width on average torque.



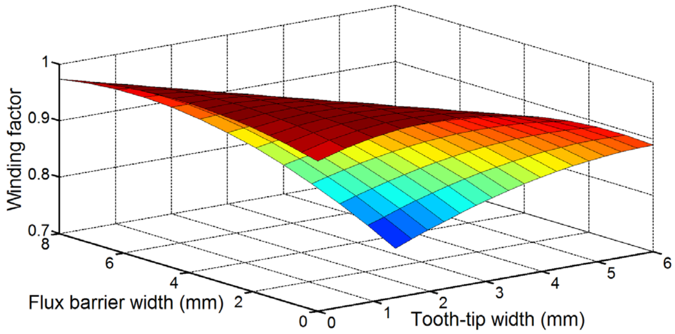
(a)



(b)



(c)



(d)

Fig. 23. Cross-sections of modular machines with flux barriers in unwound teeth. (a) With asymmetric tooth-tips on wound teeth (12S/10P). (b) With asymmetric tooth-tips on unwound teeth (12S/14P). (c) Influence of tooth-tips width and flux barrier width on winding factor (12S/10P). (d) Influence of tooth-tips width and flux barrier width on winding factor (12S/14P).

VIII. Conclusion

Based on the modularity techniques for different applications reviewed in this paper, several conclusions can be drawn:

(1) When the physical coupling exists among winding coils, the cut of stator cores is usually based on single tooth. If the stator has a large slot number, the segments can be cut based on different groups. All teeth wound winding is adopted for such kind of modular stators. However, the relative large segment number and the possible proliferation of fault could be problematic in real applications.

(2) When the segment can be isolated by tooth body and each segment consists of balanced phase windings, the coupling between segments is practically eliminated. This kind of modularity technique is preferred in large electrical machine manufacture, since the requirement of stator core assembly and fix is much lower. For fully pitched integer slot machines, this modularity technique can be inherently employed, whereas the special design is needed for fractional slot machines.

(3) The alternate teeth wound stator guarantees each coil isolated from others and therefore physically fully decoupled. The good fault-tolerant capability is the most obvious advantage for this kind of modular machine and some modified stator cores can also improve electromagnetic performance.

(4) There are many other modularity techniques, e.g. separated stator teeth and yoke.

(5) From the stator modularity techniques described in the paper, it can be found that the appropriate stator core and winding design will ease the manufacture process with potential improved performance. However, in the majority of modular IPM machines which employ fractional slot windings the reluctance torque is relatively low.

The appropriate modular machine should be designed with comprehensive electromagnetic, mechanical, and thermal consideration based on the specific requirements. As can be expected, with the development of PM machines, more advanced modularity techniques will be invented.

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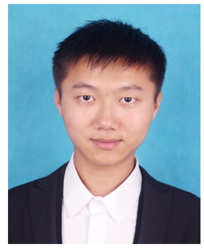

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