Overview of Permanent-Magnet Fault-Tolerant Machines: Topology and Design

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(Invited)

***Abstract*—Permanent-magnet (PM) machines have attracted a lot of interest in various applications since they have the merits of high torque density, high power density and high efficiency. However, issue of poor fault tolerance of the conventional PM machines restricts their practical applications in the field of safety-critical applications, e.g. aerospace, electric vehicle, electrical propulsion and wind power generator applications. An enormous amount of work has been done to improve the fault-tolerant capability of PM machines. This paper will review research work on PM fault-tolerant machines up-to-date, including modular design, short-circuit current limitation design, redundant design, ease of thermal dissipation of PM design, and torque enhancement design techniques. The work of this paper can provide some references for future studies and engineering applications of PM fault-tolerant machines for safety-critical applications.**

***Index Terms*—Fault-tolerant machine, modular, overview, permanent-magnet machine, torque.**

I. Introduction

IN the field of safety-critical applications such as aerospace, electric vehicle, electric propulsion and wind power generation, fault tolerance of the electrical machine is very essential because it is a core component to implement energy conversion. Switched reluctance machines have been extensively studied for aerospace applications requiring high reliability due to their inherent fault tolerance. However, torque/power density of the switched reluctance machines is much low as compared with permanent-magnet (PM) counterparts. In addition, in terms of efficiency, torque ripple, and noise and vibration, the PM machines are superior to switched reluctance machines [1-5]. Nevertheless, the PM machines do not have the natural fault tolerance as that of the switched reluctance machines. Thus, in order to combine the merit of high torque/power density of the PM machines with high fault tolerance of the fault-tolerant machines, there is a growing interest to research and develop PM fault-tolerant (PMFT) machines [5-17].

The concept of fault-tolerant machine is that it can keep continuous operation in a satisfactory manner after sustaining a fault [8-16]. The term "satisfactory" refers to as a minimum performance requirement in the event of fault occurrence. In order to achieve this target, particular design aspects on the PMFT machines should be considered as follows:

- Electrical isolation between phases
- Magnetic isolation between phases
- Implicit limiting of short-circuit current
- Physical separation of phases
- Effective thermal isolation between phases
- Number of phases

Since the concept of the PMFT machine was put forward at first in the mid 1990s [8], a huge body of published work on the PMFT machine has appeared during recent 20 years. In 2011, El-Refaie provided a thorough review and summary on the PMFT machine, with emphasis on machine design to limit short-circuit current [7]. After that, development of PMFT machine has continued. An attempt is therefore made in this paper to provide an up-to-date overview on the state-of-the-art of the PMFT machine, especially focusing on the design and analysis of machine topology.

II. Modular Design

To ensure the remaining healthy phases can works normally under fault cases, the adverse effect resulting from the faulty phases on the healthy phases should be reduced as much as possible. Modular windings and modular stator are two typical techniques to realize this target. Also, in this section, the key investigations on the PMFT machines with adoption of the two techniques will be covered.

A. Modular Windings

Mecrow *et al.* identified that to maintain the requirements for a PMFT machine drive, there should be each coil being wound around a single tooth and each slot only containing a single phase. Thus, the coils of the PMFT machine are wound alternatively [9]. Fig. 1 depicts the windings arrangement in a six-phase, eight-pole PMFT machine. As can be seen, since only alternate stator teeth carry a concentrated coil in the PMFT machine, the windings structure in the PMFT machine was referred to as modular windings in [18-25]. Fig. 2 shows the magnetic flux distribution in the PMFT machine first only due to PMs and then due to PMs and one short-circuited phase windings. It is evident that there exists a great change in flux linking the faulted phase winding when the faulted phase winding is excited. Nevertheless, the great change of magnetic flux distribution only occurs in the tooth wound faulted coil

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and its adjoining teeth, while the flux linking the healthy phase winding is not affect. In [26], the magnetic coupling issue in a PMFT machine was comprehensively investigated. It was also shown that a low magnetic coupling is very essential to design a PMFT machine. To achieve the desirable magnetic isolation, the modular winding design is also adopted.

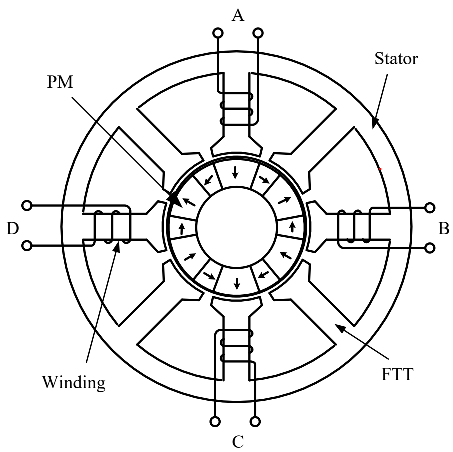


Fig. 1. Modular winding arrangement in a PMFT machine.

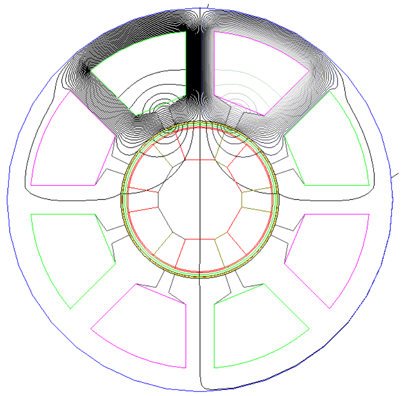


Fig. 2. Magnetic field distributions with armature current only.

In order to minimize the magnetic coupling between phases in the PMFT machines, Mitcham *et al.* proposed an approach for selecting favourable slot and pole number combinations for PMFT machines, and the basic formula of the preferred slot and pole number combinations for PMFT machines were given [13]. In [14], Bianchi *et al.* pointed out that, when the number of slots is close to poles, the mutual coupling between phases can be reduced, which further affirms the effectiveness of the findings in [13].

It should be noted that the PMFT machine with the modular windings also was termed as modular PM brushless machine in [18-25]. Atallah *et al.* presented an analytical technique for determining all possible slot and pole combinations of modular PM brushless machine, which not only contains the regular three-phase winding design but also contains a large number of multi-phase variants such as four-phase, five-phase and six-phase modular PMFT machines (Fig. 3) [18]. Wang *et al.* focused on the utility and design considerations for three-phase modular PM brushless machines. Analytical method for calculating the various electromagnetic performances such as torque, back electromotive force (back-EMF) and inductance of the machines were presented which provides a foundation for design optimization and analysis of the machines [21]. In [22], a new three-phase 24-slot 22-pole external rotor modular PM brushless machines (Fig. 4) for in-wheel applications was proposed. It was shown that the modular PM machine has a smaller number of slots for a given number of poles than that of the conventional PM machines. Thus, the modular PM brushless PM machine offers a low cogging torque and high inductance to achieve a wide speed range.

Zheng *et al.* proposed and investigated a novel five-phase surface-mounted PMFT machine [27]. Actually, the machine can be classified as a modular PM brushless machine reported in [18-25]. As shown in Fig. 5, the concentrated coils are alternatively wound on teeth, and each coil can be separated by an unwound tooth named as fault tolerant tooth (FTT). Therefore, desirable isolation between coils is achieved as the conventional modular PM brushless machine. Unlike the conventional modular PM brushless machines with three-phase winding, this machine adopted a five-phase winding, which further enhance its fault-tolerant capability. In [28], the influence of rotor poles on the electromagnetic performances of the five-phase PMFT machines was investigated. It was shown that the rotor pole number also has a great effect on the fault tolerant and torque capabilities of the five-phase PMFT machines.

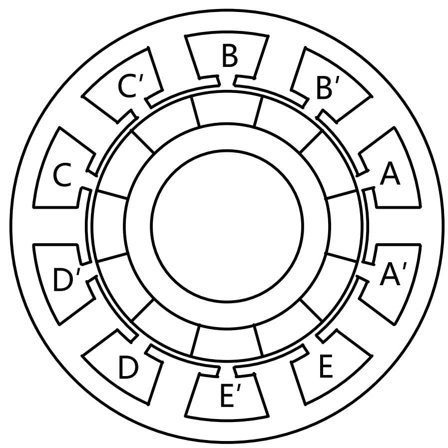


Fig. 3. Configurations of six-phase PMFT machine.

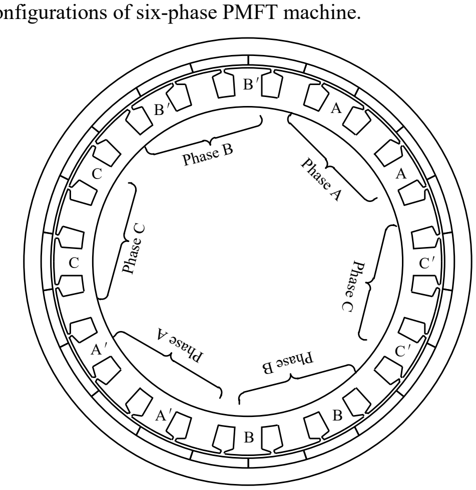


Fig. 4. Configurations of external rotor PMFT machines.

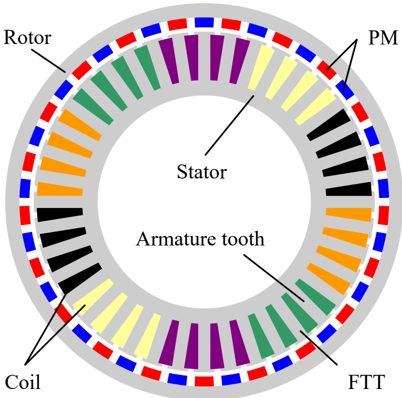


Fig. 5. Configuration of five-phase surface-mounted PMFT machine.

B. *Modular Stator*

In order to improve the fault-tolerant capability, segmented stator is increasingly employed to machine [29-37]. In [35], Li and Zhu *et al.* introduced the flux gaps into the stator teeth of modular PM machines, which formed novel modular machine topology as shown in Fig. 6. As can be seen, the new modular structure is obtained by inserting flux gaps into alternative stator. The windings are only wound on the teeth without flux gaps and are isolated by both the stator teeth without flux gaps and flux gaps, thus, high independence of each winding can be achieved, which can improve the fault-tolerant capability. In order to enhance the electromagnetic performance of the modular PM machines, the influence of the flux gaps on its electromagnetic performance was investigated. It was found that for modular PM machines with slot number larger than pole number, the introduction of flux gaps inserted into the alternative teeth reduce the average electromagnetic torque due to the reduced winding factor and flux defocusing effect. In contrast, for modular PM machines with slot number less than pole number, the average electromagnetic torque can be enhanced using proper flux gap width due to the higher winding factor and flux focusing effect. In [37], the influences of both flux gaps and stator tooth tips on the electromagnetic performances of the modular PM machines with different slot and pole number combinations were investigated. Also, some general rules considering winding factor, air gap flux density, flux focusing/defocusing effects and slot and pole number combinations were established.

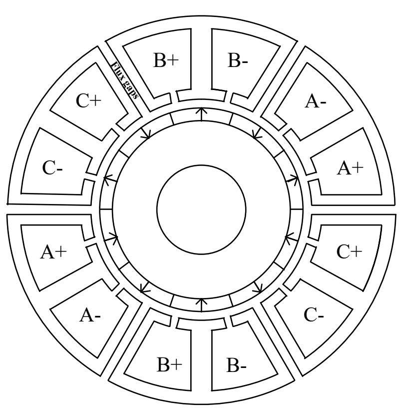


Fig. 6. Configuration of PMFT machine with modular stator.

As presented in [29-37], the modular stator design technique for improving fault-tolerant capability is effectively employed in the conventional PM machines. Considering the merits of the new class of stator-PM machines [4], [38-40], the modular stator design was also utilized for the stator-PM machines, including flux reversal PM (FRPM) and flux switching PM (FSPM) machines. A new modular linear FRPM machines was proposed in [42]. As shown in Fig. 7, a segmental mover structure was adopted for the machine, which significantly enhances its independence between phases and fault-tolerant capability.

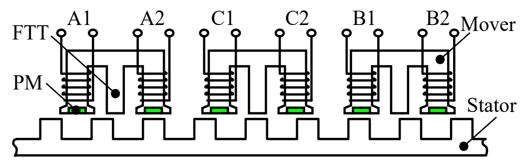
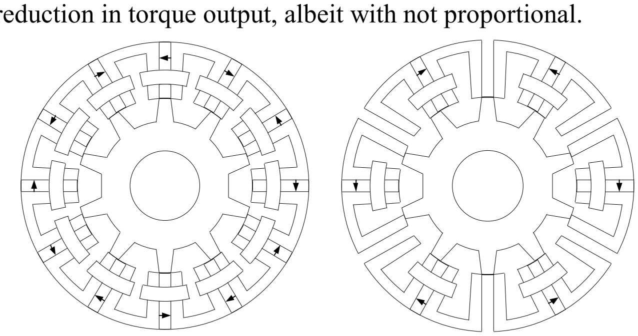


Fig. 7. Configuration of modular linear FRPM machine.

The PMs of the FSPM machine are sandwiched in the stator teeth, as shown in Fig. 8. The layout of PMs in the FSPM machine is very similar to that of the conventional interior PM machine with spoke PMs. Thus, the FSPM machine also offers the desirable flux focusing effect, which is very beneficial to improving its torque density [43-48]. As revealed in [49], the FSPM machine exhibits the highest torque density in the three types of stator-PM machines. Moreover, it was shown that the FSPM machine inherently possesses sinusoidal phase back-EMF waveform [50]. By comparing to a commercial machine used for a hybrid electric vehicle, it was also demonstrated that the FSPM machine exhibits more sinusoidal phase back-EMF waveform and good mechanical integrity [51].

Fig. 8(a) shows the structure of a typical 12 stator pole and 10 rotor pole FSPM machine. In order to achieve the desirable phase decoupling, a new FSPM machine was proposed in [52]. The new machine has the modular stator structure by removing coils and PMs on the stator teeth alternatively in the typical FSPM machine [Fig. 8(b)]. It was shown that the new FSPM machine with modular stator offers the reduced coupling between phases and improved fault tolerance. Furthermore, removing the PMs in the unwound poles incurs a substantial reduction in torque output, albeit with not proportional.



(a) (b)

Fig. 8. Configurations of (a) conventional FSPM machine and (b) fault-tolerant FSPM machine with modular stator.

The linear type of the rotating FSPM machine with modular stator was also investigated in [53]. As can be seen in Fig. 9, the mover of the new machine is constituted of several modular units, in which each unit consists of two U-shaped lamination cores, one piece of PM and one set of concentrated coil. Thus, the new topology is named as modular linear FSPM machine [53]. It was also found that replacing the PMs in the unwound stator poles with flux barriers can enhance the fault-tolerant capability and PM utilization ratio of the FSPM machine. Furthermore, it was shown that the modular linear FSPM machine can offer 74% improvement of force density as compare with the conventional one when the same PM usage is applied for the two machines. It is further demonstrated that the new modular linear FSPM machine possesses the merit of high PM utilization ratio.

In addition to introducing the non-magnetic flux barrier into the linear FSPM machine to achieve the desirable modularity, the magnetic flux barrier can also be employed for the linear FSPM machine to form the modularity [54-56], as shown in Fig. 10. Like the machine with non-magnetic flux barrier, the one with magnetic flux barrier retains the merits of high fault-tolerant capability. Moreover, manufacturing cost of the machine with magnetic flux barrier can be reduced since the two U-shaped lamination cores and one flux barrier of the machine with non-magnetic flux barrier can be replaced with only one E-shaped lamination core.

By adopting the aforementioned modular mover design technique for the linear FSPM machine, end effect in the primary of the machine can be eliminated. Thus, adverse effect on back-EMF of coils at the end of primary can be minimized. Nevertheless, inherent merit of complementarity of magnetic circuit of any phase in the modular linear FSPM machine is lost since the coils belonged to one phase has the same position relative to the stator [57]. Consequently, the modular linear FSPM machine suffers from asymmetrical back-EMF waveforms, large cogging force and large force ripple. In order to solve above issues, a new kind of complementary and modular linear FSPM machine was proposed in [57] (Fig. 11). The key of the machine is to artfully adjust the dimension of the flux barrier to achieve the complementary magnetic circuit. It was found that by utilizing the new design of the flux barrier, the new modular linear FSPM machine definitely not only retains the desirable decoupling between phases but also offers the symmetrical back-EMF waveforms, reduced cogging force and smooth force [58-61].

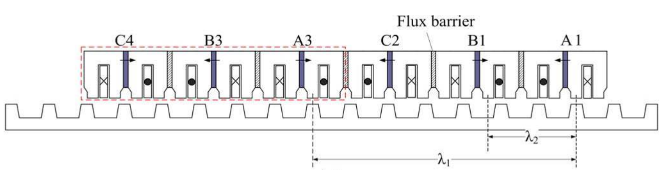


Fig. 9. Configuration of modular linear FSPM machine with non-magnetic flux barrier.

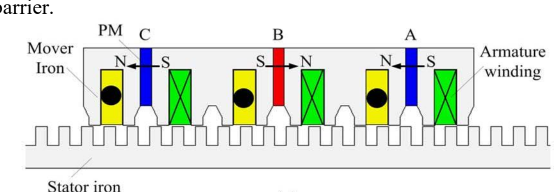


Fig. 10. Configuration of modular linear FSPM machine with magnetic flux barrier.

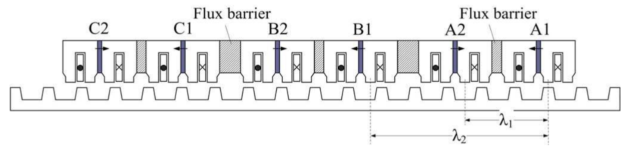


Fig. 11. Configuration of complementary and modular linear FSPM machine.

III. Short-Circuit Current Limitation Design

Short-circuit current in a PMFT machine should be limited to avoid causing catastrophic damage when it is under short-circuit fault. The short-circuit current of the PMFT machine is generally designed with a value which is less than or equal to the rated current in the normal operation condition. The key of reducing the short-circuit current is to increase inductance of the PMFT machine.

EL-Refaie *et al.* presented detailed analysis, design, and test results of a 175-kW main power PMFT generator for aerospace applications [62]. In order to meet the requirement of high fault-tolerant capability, the machine is designed with a high inductance to limit short-circuit current. Fig. 12 shows the configuration of the PMFT generator. The slot opening of the stator is filled with magnetic wedges made from iron-epoxy resin with relative permeability of about 3. By regulating the ratio of iron to epoxy, the relative permeability and inductance can be adjusted to the desirable values so as to limit the short-circuit currents. Particularly, Gerada *et al.* proposed a novel closed-slot PMFT machine for fault-tolerant drivetrains [63], (Fig. 13). It was shown that the closed-slot design significantly increase phase inductance so as to limit the short-circuit current as well as to reduce the rotor eddy-current losses. However, it was also pointed out that the high magnetic saturation in the tooth tips due to the closed-slot design is a key issue, as shown in Fig. 13.

In order to increase winding inductance and reduce short-circuit current, a FSPM machine with a semiclosed-slot stator was proposed in [64]. Fig. 14 shows the semiclosed-slot stator structure. As can be seen, the desirable magnetic and physical isolations between coils are achieved due to the coils wound alternative teeth. Besides, owing to the reduction of slot openings in the semiclosed-slot stator, the machine is easier to realize a high inductance to restrain short-circuit current. However, it should be noted that the semiclosed-slot stator design also increases the flux leakage and cuts down the output torque.

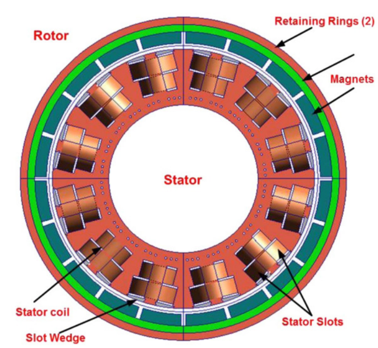


Fig. 12. Configuration of PMFT generator with open-slot stator and magnetic wedges filled in slot openings.

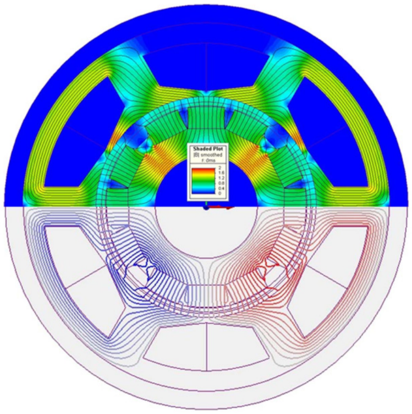


Fig. 13. Configuration of six-slot four-pole closed-slot PMFT machine together with open-circuit flux distributions.

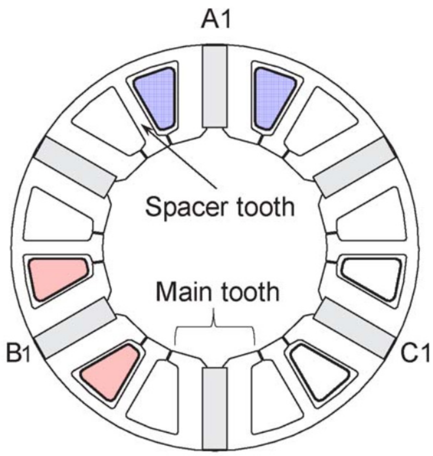


Fig. 14. Configuration of semiclosed-slot stator of PMFT machine.

IV. Redundant Design

A. Multiphase Windings Design

Multiphase machine refers to the machine having phase number larger than three. Compared to the regular three-phase machine, the multiphase machine possesses a lot of advantages due to the increase of phase number, such as power splitting, lower torque ripple, lower power rating per phase and better fault-tolerance [65-67]. Particularly, the high phase number give rise to the additional degrees of freedom, which can be effectively utilized for postfault operation strategy to deal with various faults. In [68-72], fault-tolerant control strategies of five-phase PM machines were proposed. It was shown that the multiphase PM machine has excellent fault-tolerant capability. In [73-76], the modular winding technique was introduced into the multiphase PM machines, thus forming the multiphase PMFT machines. It was shown that by combining the modular winding and multiphase winding techniques, the fault-tolerant capabilities of the machines were greatly enhanced. Owing to the merits of the multiphase winding, the FSPM machines with higher phase numbers, including four-, five-, six-, nine-, and twelve-phase variants were extensively investigated [77-81]. Two five-phase fault-tolerant FSPM machines having 18 and 19 rotor poles were proposed and compared in [82]. As shown in Fig. 15, the two machines share the same modular winding structure, thus offering the desirable independence between phases. It was found that both machines retain the merits of FSPM machines and multiphase machines, but also achieve reduced cost and enhanced fault-tolerant capability. Also, compared with the machine with 18 rotor poles, the one with 19 rotor poles exhibits more symmetrical and sinusoidal back-EMF waveform and lower cogging torque, while it suffers from increased unbalanced magnetic force due to the adoption of odd rotor poles. In [83], vibration and noise in the 19 rotor poles fault-tolerant FSPM machine under healthy and faulty conditions were predicted. It was shown that the by adopting an appropriate postfault control strategy, the machine maintains the same average torque. However, the vibration and noise under fault-tolerant condition becomes more severe than that of under healthy condition.

In addition to the modular multiphase winding PM machines, the multiphase PM machines without adopting the modular windings can also achieve certain fault-tolerant capability, and considered as good solutions for high reliability. It is because that the multiphase winding structure increases the redundant capability. Regarding the multiphase PM machine without adopting the modular winding, distributed winding is usually applied. In [68], Parsa *et al.* proposed interior PMFT machines with five-phase fractional slot distributed winding. It was shown that, by using the five-phase fractional slot distributed winding, the proposed machine has a very low torque ripple. Fig. 16 shows the configuration of the proposed machine. As can be seen, it has 4-pole interior PM rotor and 15-slot accommodating for the five-phase fractional slot distributed winding. In [84], Lu *et al.* presented the design procedure of a five-phase brushless DC PM machine for an electrohydrostatic actuation system, where the multiphase distributed winding were also adopted to achieve high reliability. Although the multiphase distributed winding can offer certain fault-tolerant capability owing to the high phase number, the distributed winding increases the mutual coupling and reduces the independence between phases which limits its fault-tolerance. Nevertheless, the distributed winding provides the potentials to utilize reluctance torque in postfault operation which is very essential for PM machines with high reluctance torque [85].

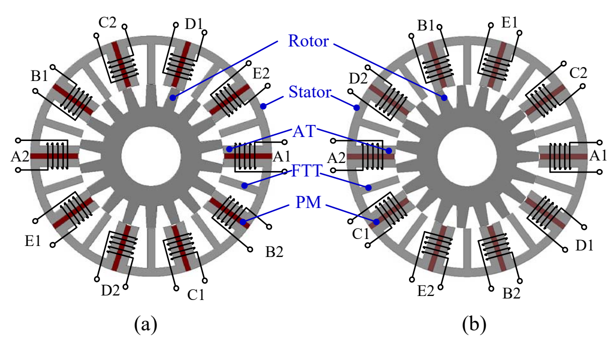


Fig. 15. Configurations of five-phase FSPM fault-tolerant machines. (a) 18 rotor poles. (b) 19 rotor poles.

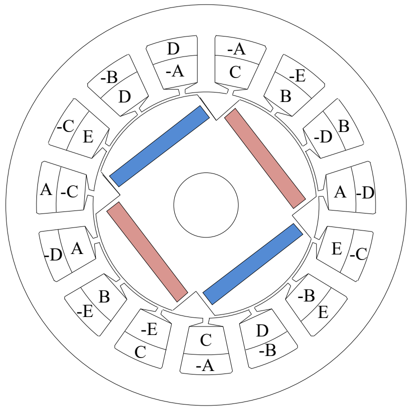


Fig. 16. Configuration of five-phase interior PM machine.

B. Multiple Three-Phase Technique

Multiphase PM machine with the high phase number can offer the high fault-tolerant capability, while the multiphase drive generally need expensive custom solutions, as presented in [86-97]. PM machines with multiple three-phase winding can be driven by multiple standard three-phase converters, and thus avoiding the use of custom and expensive converters [91]. Also, the PM machines with multiple three-phase winding retain the merits of the additional freedom of control. Therefore, the multiple three-phase winding is considered as an effective technique to improve the fault tolerance of the PM machines. The researches on the multiple three-phase PM machines are mainly focused on the machines with dual three-phase winding [86-92]. Fig. 17 shows the dual three-phase PM machine drive [90]. As can be seen, each of the two three-phase windings is fed with separate three-phase inverter. Therefore, it avoids the use of custom and expensive converter, which is different from the multiphase machine drives such as five-phase and seven-phase machines. Barcaro *et al.* analyzed the feasible of the dual three-phase winding applied to the nonoverlapped-coil fractional-slot concentrated winding PM machines. Also, performances including torque behavior, overload capability and thermal limit under both open-circuit and short-circuit faults of a fractional-slot dual three-phase PM machine were evaluated, and experimental tests were carried out for verification [91].

The dual three-phase winding technique was also employed to FSPM machine drives, where the dual three-phase winding configuration was named as redundant winding. A new FSPM machine with redundant winding, termed as redundant FSPM machine, was proposed in [94], [95]. Fig. 18 shows the configuration of the redundant FSPM machine. As can be seen, it shares the same 12-stator-pole and 10-rotor-pole as the existing FSPM machine in [50]. The difference between the proposed redundant machine and existing machine is their configurations of coil connection. For the redundant machine, the four coils belonging to one phase are divided into two groups, thus forming two channels, namely, A_I and A_{II} in terms of Phase A, as shown in Fig. 18. Also, each channel has its own power converter and controller. Thus, its fault-tolerant capability is significantly enhanced. Fault tolerant control strategy for the redundant FSPM machine was also proposed and implemented, showing that satisfactory performances are achieved when the machine is operated on fault-tolerant mode [94], [95].

Very recently, Wang *et al* proposed a PMFT machine drive based on permanent magnet assisted synchronous reluctance machine, which adopts a triple three-phase windings [96]. The triple three-phase winding configuration is set as shown in Fig. 19. It can be seen that the three three-phase windings has low coupling between them. Furthermore, the risk of PM magnetic field cannot be turned off under faulty condition is minimized without compromise in torque density and efficiency. This is achieved by using a synchronous reluctance rotor and embedded PMs which can yield a high reluctance torque.

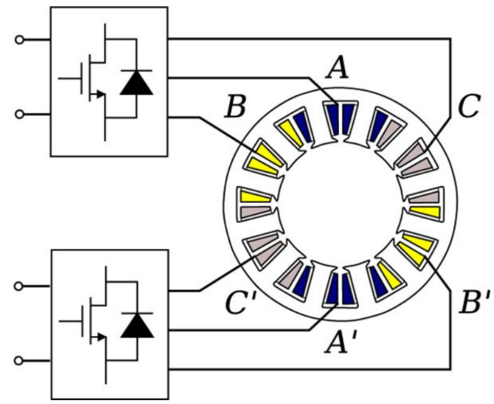


Fig. 17. Configuration of dual three-phase machine drive.

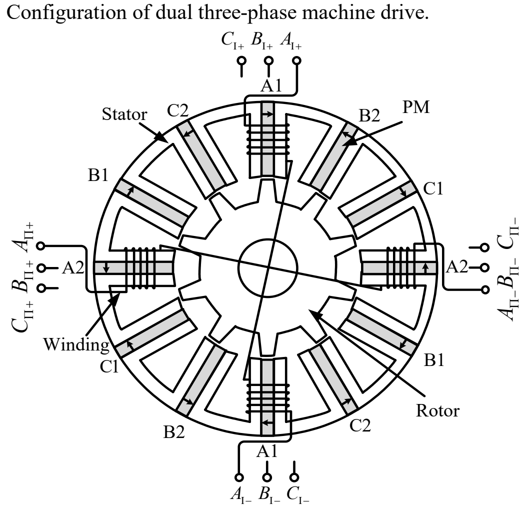


Fig. 18. Configuration of redundant FSPM machine.

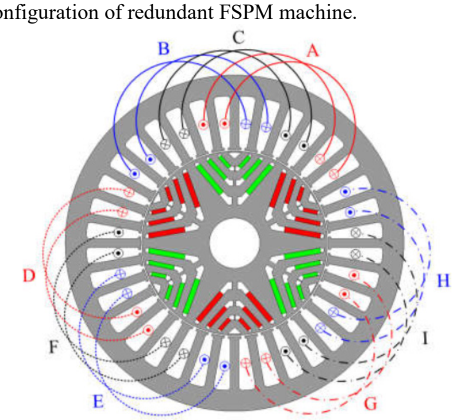


Fig. 19. Configuration of triple three-phase winding machine.

C. Multiple Machine

In [16], to achieve an imperative fault-tolerant capability for electric power steering application, a redundant solution with two machines on the same shaft was proposed, as shown in Fig. 20. As can be seen, the requirement of linear movement of the steering rack was converted by the rotating movement of the machine. The dual machine can still operate even when one inverter or one machine occur complete loss. Thus, the dual machine system offers excellent fault-tolerant capability. It was shown that the interior PMFT machine has a low braking torque after a three-phase short-circuit fault. Also, the machine parameters influencing the maximum braking torque were determined, which can be used in design of the machine.

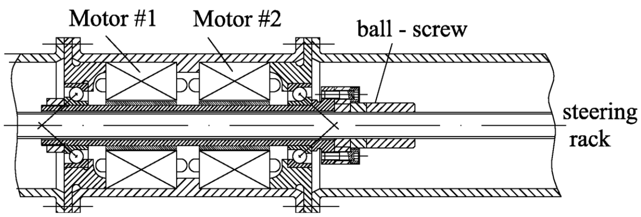


Fig. 20. Configuration of dual machine drive.

V. Ease of Thermal Dissipation of PMs

As for the PMFT machines, in order to maintain the reasonable performances under fault-tolerant operations, the currents of the phase windings should be regulated to suppress the adverse effects resulted from the faults. Usually, the fault-tolerant currents and total losses are increased. It may leads to the occurrence of irreversible demagnetization of the PMs due to the high temperature under fault-tolerant operation. For the conventional PMFT machines, their PMs are located on the rotor. It is very difficult to manage the temperature rise of the PMs since the PMs rotate with the rotor. Thus, it not only further increases the risk of the occurrence of the irreversible demagnetization under fault-tolerant operation [99], [100]. Furthermore, the presence of PMs on the rotor of the PMFT machines significantly limits the maximum rotational speed of rotor to ensure the PM not dropping from the rotor, which leads to the reduction of the power density. The emerged new stator-PM machines can overcome these issues existed in the conventional PM machines having PMs on the rotor [6]. The family of the stator-PM machine is composed of three members, viz., doubly-salient PM (DSPM) machine, FRPM machine and FSPM machine, as shown in Fig. 21. It can be seen that the three machines have similar rotor structure and all excitation sources are on the stator, which results in a good thermal management of the PMs and robust rotor structure suitable for high speed operation. Therefore, by borrowing the concept of the stator-PM machines into the PMFT machines, the improvement of thermal dissipation of PMs and power density can be expected.

In addition to all excitation sources on the stator, the stator-PM machines have the feature that concentrated windings are generally adopted. Thus, they inherently possess fault-tolerant capability to some extent. In [101], fault-tolerant performances including both internal and external faults of the stator-PM machines drive was analyzed. Various fault-tolerant control strategies were proposed to improve the performance of the machine drive under faulty conditions. Both simulated and experimental results verified that the effectiveness of the fault-tolerant characteristic of the stator-PM machine drives.

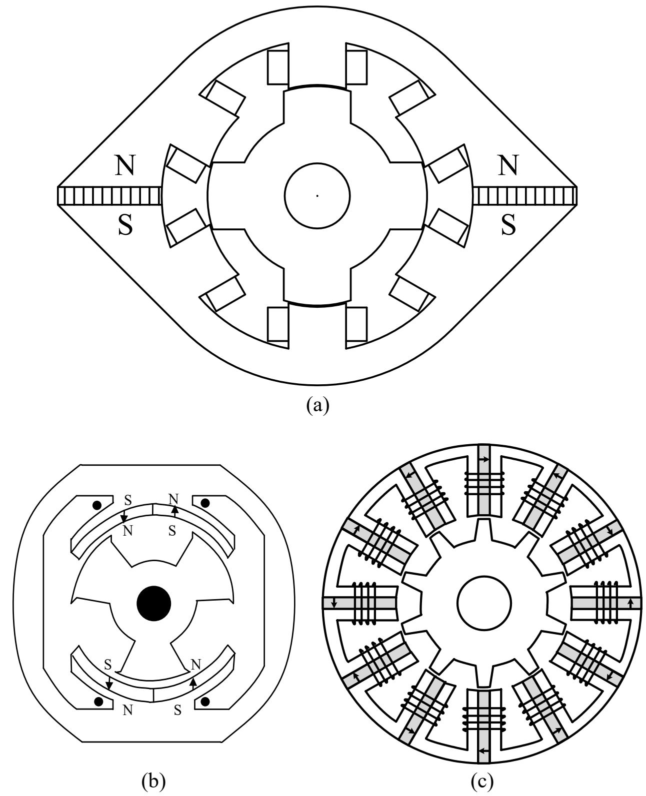


Fig. 21. Configurations of basic stator-PM machines. (a) DSPM machine. (b) FRPM machine. (c) FSPM machine.

VI. Torque Enhancement Design

A comparative study of PMFT and switched reluctance machines was conducted in [9]. It was revealed that the PMFT machine offers a greater torque density than that of the switched reluctance machine, even when the PM machine is compromised to realize fault tolerance. Also, it is pointed out that the torque density of the PMFT machine may be reduced in order to achieve the fault-tolerance. To improve the torque density of the PMFT machines, a lot of techniques of torque improvement for PMFT machines have been proposed.

A. Open-Slot Stator Structure

Wrobel and Mellor *et al*. investigated open-slot modular PM brushless machines (Fig. 22), in which the open-slot stator offers high slot fill factors since the open-slot stator greatly simplifies manufacture and a preformed coil is possible [102-104]. Thus, by using the open-slot stator, improved torque density of the PMFT machine can be obtained. In [103], the open-slot modular PM brushless machines with different slot and pole number combinations were presented for which the winding factor is maximal and torque ripple is minimal. It was shown that despite an open-slot stator structure, its cogging torque and output torque ripple can be significantly suppressed. Thus, the open-slot stator is also a viable proposition for the modular PM brushless machine. Furthermore, the open-slot modular PM brushless machine with single layer concentrated winding potentially has several advantages in heat transfer as compared to that of conventional machine topology [104].

In [107] and [108], E-core FSPM machines with open-slot and semiclosed-slot stators were proposed as shown in Fig. 23. The operation principle and influence of stator and rotor pole combinations of the E-core FSPM machines were investigated in [105]. It was shown that the adoption of the E-core open-slot stator structure is conducive to increasing slot area and saving expensive PM usage, which results in improvement of torque and PM utilization.

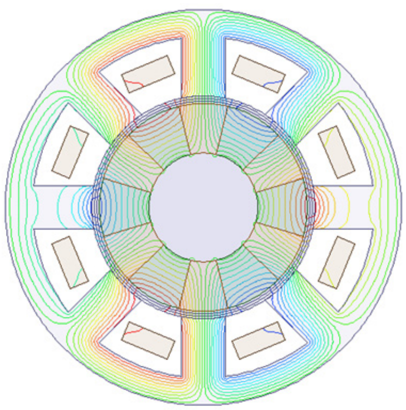


Fig. 22. Flux distributions of open-slot PMFT machines.

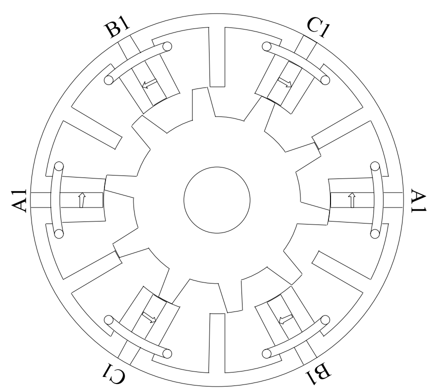


Fig. 23. Configurations of E-core FSPM machines with open-slot stator.

B. Unequal Tooth Width Structure

As for the PMFT machine with the modular winding, the unequal tooth structure is an effective technique to improve its torque density. In [24], a modular winding PMFT machine with unequal tooth widths and alternative teeth wound on wider teeth was proposed as shown in Fig. 24(b). It was shown that the new design can maximize the flux linkage and torque as compared to its conventional counterparts as shown in Fig. 24(a). In [25], the electromagnetic performances of the PMFT machine with unequal tooth widths and with different slot and pole number combinations were investigated. It was also shown that the PMFT machine with unequal tooth widths offer a more trapezoidal phase back-EMF waveform suitable for brushless dc operation, a higher torque capability, and a lower torque ripple than similar PMFT machines with equal tooth widths, while these benefits gradually diminish as the increase of the pole number, which is due to the effect of interpole leakage flux.

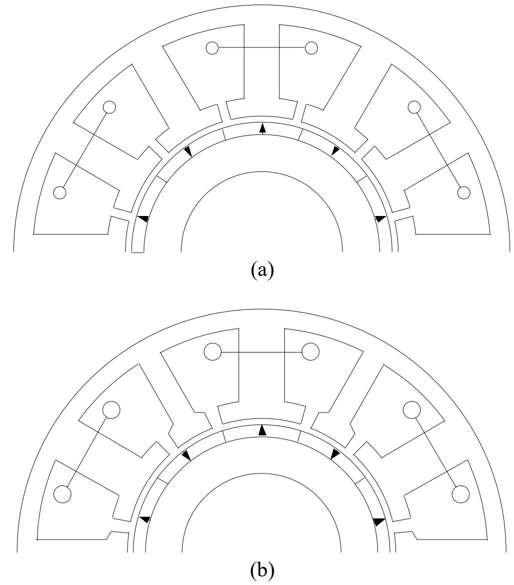


Fig. 24. Modular winding PMFT machine with (a) equal tooth width and (b) unequal tooth width.

C. Multi-Tooth Structure

Multi-tooth stator structure is widely employed for torque improvement [106-108]. In [108], a new fault-tolerant FSPM machine with multi-tooth was proposed. As illustrated in Fig. 25, unlike the conventional FSPM machine, the proposed machine adopt a multi-tooth stator structure, in which each stator pole is split into 2-stator so as to form the multi-tooth stator structure. It was shown that the proposed machine offers higher torque density and lower torque ripple as compared to that of the conventional one. Also, it was found that the multi-tooth stator is beneficial to increasing winding inductance, thus inhibiting the short-circuit current. Furthermore, the fault-tolerant capability of the proposed machine was further enhanced by the introduction of spacer tooth as shown in Fig. 25. Last, twisted-rotor structure was adopted for the machine to compensate unbalanced magnetic circuit. As a result, the machine not only possesses high fault-tolerant capability but also exhibits symmetrical and sinusoidal back-EMF waveform.

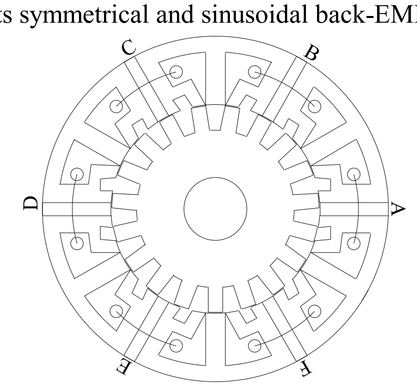


Fig. 25. Configuration of multi-tooth fault-tolerant FSPM machine.

D. Flux Concentration Rotor Structure

Flux concentration rotor structure can offer an enhanced PM air-gap flux density and magnetic loading so as to achieve an improved torque density. PMs arranged in a Halbach array can maximize the PM air-gap flux density and realize the flux concentration. In [11], Mecrow *et al.* designed and tested a four-phase modular winding PMFT machine for an engine fuel pump, in which the PMs are arranged in a Halbach array considering the merits of torque improvement of Halhach array. Zhao *et al*. proposed Halhach vernier PMFT machines for safety-critical applications. It was shown that, by using the Halhach array, the torque of the vernier PMFT machines are improved [109]. Also, their losses and efficiencies are reduced and improved, respectively.

The interior PM rotor structure can also give rise to the flux concentration effect. In [110-112], Liu *et al*. proposed and investigated two five-phase interior PMFT machines. Fig. 26 shows the configurations of the two five-phase interior PMFT machines. It can be seen that the two machines adopt the two different interior PM rotor structures, namely, spoke-type and V-shape PM arrays, respectively. Comprehensive comparison between the two machines was carried out in [112]. It was shown that, by using the interior PM rotor structures, their torque densities and maximum flux-weakening speed ranges are enhanced and extended, respectively. Also, it was shown that the spoke-type PM arrays has a better flux concentration capability which can reduce the machine cost owing to the reduction of PM usage.

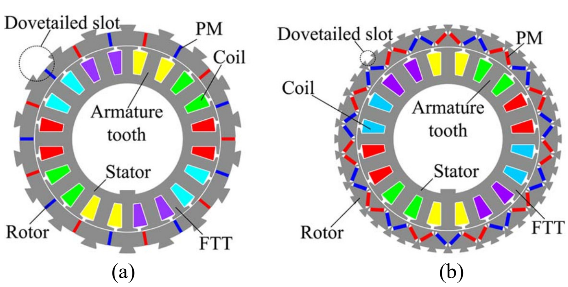


Fig. 26. Configurations of two five-phase interior PMFT machines. (a) Spoke-type. (b) V-shape.

E. Axial-Flux Structure

Axial-flux PM machine is featured of the large ratio of outer diameter to axial length, which is superior to the radial-flux one in terms of high torque density and high space utilization. Thus, it is very attractive for high torque density applications [113-118]. By combining the concepts of E-shape core with axial field, Lin *et al*. proposed a new axial field fault-tolerant FSPM machine in [117], as shown in Fig. 27. It was shown that the proposed machine exhibits high torque density and high fault-tolerant capability. Like the FSPM machine in [117], the FSPM machine in [118] also adopted axial field to increase torque/power density. Besides, high fault tolerance is achieved by adopting phase-group concentrated coils and dual-three phase channel.

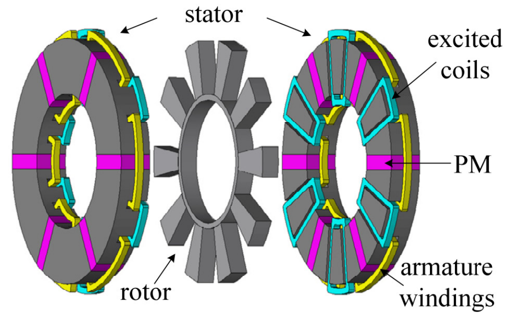


Fig. 27. Configuration of axial-field fault-tolerant FSPM machine.

F. Vernier Structure

A novel high-performance magnetic gear was proposed by Atallah and Howe in [119]. As shown in Fig. 28, it consists of inner rotor, outer rotor, ferromagnetic pole-pieces and two air-gaps. The ferromagnetic pole-pieces between the inner rotor and outer rotor are worked as flux modulation pole to regulate PM magnetic fields to yield various space harmonic magnetic fields. Owing to the introduction of ferromagnetic pole-pieces, the magnetic gear is operated based on flux modulation effect. Thus, various space harmonic components in the air gap can be utilized so as to yield a high torque density. It was pointed out that the magnetic gear can offer a torque density exceeding 100 kNm/m^3, which is much higher than that of standard PM machine.

In [120], [121], Chau *et al.* proposed a new magnetic-geared PM machine on the basis of the concept of magnetic gear. It was shown that the magnetic-geared PM machine retains the merit of high torque density of the magnetic gear, while it suffers from a complicated structure involving three air-gaps. In order to simplify the structure, a variety of new magnetic-geared PM machine is developed in [122-127].

In addition to the magnetic-geared PM machines in [128]-[143], Vernier PM machines were also operated based on the flux modulation principle, as revealed in [128-143]. Besides, it was demonstrated by Qu *et al.* that the vernier PM machines inherently possess higher torque and lower torque ripple [131]. More importantly, it is worthwhile to note that the vernier PM machines take advantage of simple structure. Fig. 29 illustrates two kinds of typical vernier PM machine topologies. As can be seen, both the vernier PM machines possess simple mechanical structures, which are similar to conventional PM machines. It can be observed that both the vernier PM machine adopt large slot opening to form the flux modulation poles so as to achieve the desirable flux modulation effect.

In general, owing to the desirable flux modulation effect, the vernier PM machines inherently offer high torque while they suffer from some shortcomings including low power factor and poor fault tolerance. In order to mitigate the low power factor, Qu *et al.* proposed a new dual-stator spoke-array vernier PM machine in [137]. It was shown that the machine exhibits high power factor, viz., ~ 0.92, and significantly high torque density. Besides, a new single-stator spoke-array vernier PM machine was proposed by Cheng *et al.* [138], which enhances the power factor and torque density.

As regards fault tolerance, the feature of high inductance and low PM flux linkage of the vernier PM machine is very conducive to cutting down the short-circuit current. Thus, the vernier PM machine has indeed certain fault-tolerant capability even without particular design consideration of fault tolerance. But, the fault-tolerant capability of the vernier PM machine is poor from the view of independence between coils since there exists severe coupling between coils [140]. In order to enhance the fault tolerance and retain high toque, Liu *et al*. proposed a new five-phase vernier PMFT machine [141], as illustrate in Fig. 30(a). It is evident that the vernier PMFT machine adopts modular winding to realize the high independence between phases. Also, the five-phase winding provides increased degrees of freedom than that of regular three-phase windings, thus enhancing its redundancy. Despite achieving the high torque and fault-tolerant capability simultaneously, the vernier PMFT machine suffers from high iron loss, low poor factor and low PM utilization [141-143]. In order to alleviate these issues, Zhao *et al*. proposed a new kind of vernier PMFT machine based on a new hybrid stator structure [143], as shown in Fig. 30(b). It was found that by utilizing the new hybrid stator design, the PM pole-pairs of vernier PMFT machines can be significantly reduced without reducing torque density. Also, the power factor and iron loss can be improved and reduced, respectively.

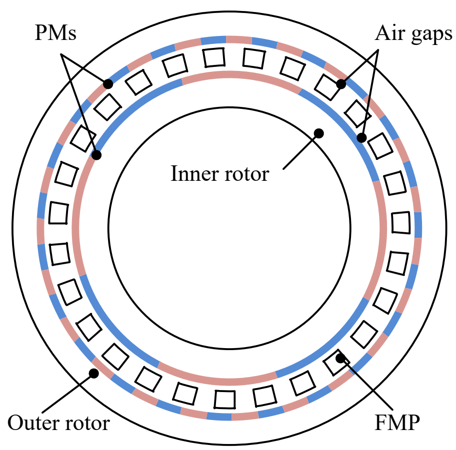
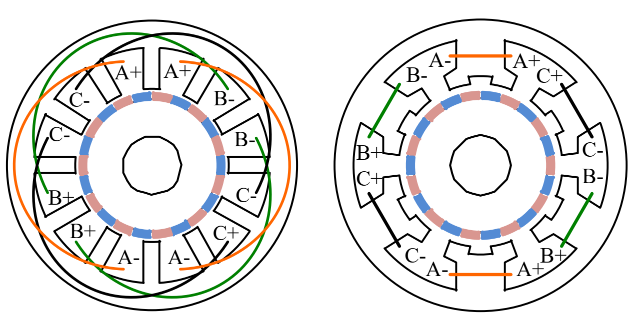
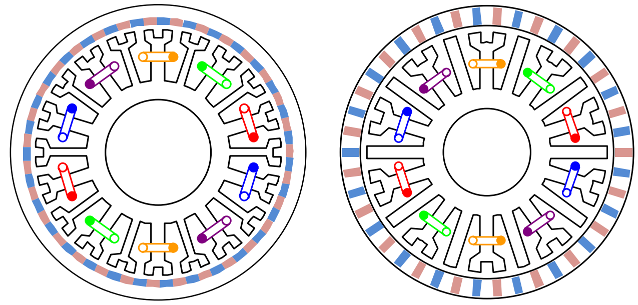


Fig. 28. Configuration of high performance magnetic gear.



(a) (b)

Fig. 29. Configurations of vernier PM machines with conventional stator structures. (a) Open-slot stator. (b) Split-slot stator.



(a) (b)

Fig. 30. Configurations of five-phase vernier PMFT machines. (a) Split-tooth stator. (b) Hybrid stator.

VII. Conclusion

This paper has presented the state-of-the-art of the PMFT machines, with particular emphasis on topology and design. At first, the fault-tolerant concept of the PMFT machine has been introduced. Then, the techniques of reducing the coupling and improving the independence between phases of the PMFT machines, i.e., modular winding and modular stator designs have been surveyed. Next, the techniques of limiting the short-circuit current of PMFT machines has been surveyed. It is found that the reducing the slot opening and even closing the slot opening is a major design technique of reducing the short-circuit current. Also, it is found that, apart from the modular design, multiphase technique can offer fault-tolerance owing to its redundancy. The new class of stator-PM machine has been introduced. It is shown that the machine not only offer fault-tolerance but also possesses improved thermal dissipation of PMs, which provides a good potential to achieve high power density/torque density. Finally, the torque enhancement design technique of the PMFT machine has been surveyed.

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