New Topologies of High Torque Density Machine Based on Magnetic Field Modulation Principle

Yan Yue, Shaofeng Jia, *Senior Member*, *IEEE*, and Deliang Liang, *Senior Member*, *IEEE*

***Abstract*—With the increasing demand for high torque density in motors, more and more new topologies emerge. Furthermore, the magnetic field modulation principle is widely concerned and has evolved into an effective analysis method for studying the new motor topology. This paper introduces the principle of magnetic field modulation. And the research on high torque density in recent years is reviewed from the perspective of magnetic field modulation, including permanent magnet vernier machine (PMVM), flux reverse machine (FRM), flux switching machine (FSM), dual permanent magnet (DPM) machine, and DC biased machine. The principle of magnetic field modulation makes it possible to propose higher torque density topologies in the future.**

***Index Terms*—High torque density, Magnetic field modulation, Vernier machine, Dual permanent magnet machine, DC biased machine.**

I. INTRODUCTION

SINCE the motor was invented over a century ago, its torque density, power density, efficiency, low noise, and other performance have all been continuously improved in response to people's growing demand, especially more demanding requirements and expectations in the present. High power density has always been the aim of people in the current applications of motors to create higher performance in aerospace[1], navigation[2], industrial applications[3], and electric vehicles[4].

It can increase the power density by increasing the speed[5] and torque density of the motor. The speed of the motor is often limited by application scenarios, so the improvement of motor torque density is particularly important. The high torque density of the motor means high electrical load, high magnetic load, and excellent topology. High electrical load and high speed are bound to increase the loss of the motor. The heat caused by the loss will be more obvious. High temperature is not conducive to normal motor operation and can cause insulation aging and even burn the motor, so it is necessary to reduce loss and improve effective cooling to improve power density. At the same time, the study of advanced motor materials working at high temperatures and permanent magnetic materials working at high magnetic loads is also of great significance to increasing power density. In addition, the key to fundamentally improving the motor torque density is the highly advanced and excellent topology.

In recent years, the principle of magnetic field modulation has been widely studied. In order to improve the power density of the motor, more advanced topologies are proposed on the basis of expounding the operation principles of some types of motors by the magnetic field modulation principle. From this paper, the topologies of high torque density motors are reviewed from the perspective of the magnetic field modulation principle. The structure of this paper is as follows: The second chapter introduces magnetic field modulation and explains its principle. Chapter III introduces a series of current popular motor topologies, including permanent magnet vernier machine (PMVM), flux reverse machine (FRM), and flux switching machine (FSM). The fourth chapter introduces the dual permanent magnet (DPM) machine based on the magnetic field modulation principle. Chapter V introduces the recent DC biased machine.

II. PRINCIPLE OF MAGNETIC FIELD MODULATION

A. *Introduction of Magnetic Field Modulation*

In the 1960s, Professor C. H. Lee proposed a magnetic vernier reluctance machine[6]. The machine used the dual-salient pole structure of the stator and rotor to produce the air gap magnetic field distribution of the displacement triangle wave. When the rotating magnetic field is fed into the air gap, the rotor will rotate at a speed that is a fixed proportion of the speed of the rotating magnetic field, so as to realize electromagnetic deceleration.

Besides, in 2002, K. Atallah and D. Howe proposed a coaxial magnetic gear[7], which is equipped with different pole pairs of permanent magnets in both the high-speed rotor and the low-speed rotor, and a static magnetic modulation ring is placed in the middle to change the conduction of the air gap, to realize variable speed and variable torque transmission between the high-speed rotor and the low-speed rotor. Afterwards, the concept of magnetic field modulation was proposed in [8], and the operation principle of magnetic gear was analyzed by magnetic field modulation.

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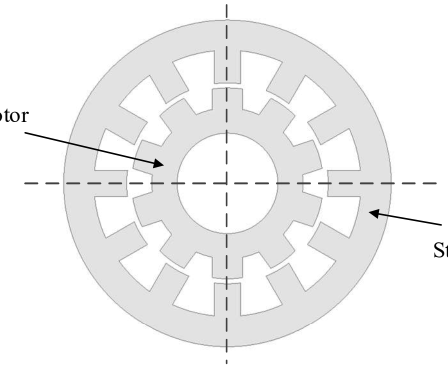

Fig. 1. The magnetic vernier reluctance machine[6].

Therefore, the magnetic field modulation effect is also called the magnetic gear effect. In [9], R. Qu proved that magnetic gear and vernier machines have the same operation principle, and a more detailed demonstration of the evolution process of magnetic gear to vernier machine compared the advantages and disadvantages of various topologies. Since then, the principle of magnetic field modulation has been widely studied and applied to various new machine topologies.

B. Principle of Magnetic Field Modulation

The principle of magnetic field modulation can be explained by the operation principle of coaxial magnetic gear. As shown in Fig. 2, the coaxial magnetic gear is divided into three layers. The inner and outer layers are the inner rotor and outer rotor with different pole pairs of surface-mounted permanent magnets. The middle is the magnetic regulating ring, which acts as the modulation tooth in the magnetic field modulation principle and realizes the coupling of different pole pairs magnetic fields of the inner rotor and outer rotor.

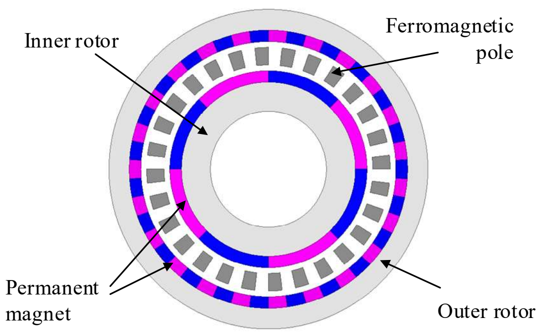

Fig. 2. The coaxial magnetic gear[7].

Firstly, the magnetomotive force (MMF) generated by the permanent magnets of the outer rotor can be expressed by a series of Fourier equations as

$$F_{opm}(\theta_s,t)=\sum_{i}^{\infty}F_{opmi}\sin[iP_{opm}(\theta_s-\omega_o t)+\varphi_o] \tag{1}$$

$$F_{ipm}(\theta_s,t)=\sum_{j}^{\infty}F_{ipmj}\sin[jP_{ipm}(\theta_s-\omega_i t)+\varphi_i] \tag{2}$$

where F_{opm}, F_{ipm} are the MMF of permanent magnets in outer rotor and inner rotor, θ_s is the space angle, i, j are the harmonic orders, $F_{\mathrm{opm}i}$, $F_{\mathrm{ipm}j}$ are the amplitude of the i^{th}, j^{th} harmonics of MMF of permanent magnets, P_{opm}, P_{ipm} are the pole pair number of permanent magnets in outer rotor and inner rotor, ω_o, ω_i are the mechanical velocity, and φ_o, φ_i are the initial phase angle of permanent magnet MMF.

The MMF generated by the permanent magnet will be modulated by the static modulation ring because of the change in the air gap permeance. The permeance around the air gap circle can be expressed as

$$\Lambda_m(\theta_s)=\Lambda_{m0}-\sum_{m=1}^{\infty}\Lambda_{mm}\cos(mN_m\theta_m+\varphi_m) \tag{3}$$

where Λ_{m0} is the fundamental amplitude of air gap permeance, m are the harmonic orders, Λ_{mm} is the amplitude of the m^{th} harmonics of air gap permeance, N_{m} is the tooth number of static modulation ring, and φ_m is the initial phase angle of permeance alternating component.

Based on the simplified magnetic circuit method, the air gap magnetic field can be obtained by multiplying the excitation MMF and the air gap permeance, so the synthetic magnetic field from the outer rotor permanent magnet field, modulated by the static modulation ring is

$$\begin{aligned}B_{opm}(\theta_s,t)&=F_{opm}(\theta_s,t)\Lambda_s(\theta_s)\\&=\sum_{i=1}^{\infty}F_{opmi}\sin[iP_{opm}(\theta_s-\omega_o t)+\varphi_o]\\&\quad\times\left[\Lambda_{m0}-\sum_{m=1}^{\infty}\Lambda_{mm}\cos(mN_m\theta_s+\varphi_m)\right]\\&=\sum_{i=1}^{\infty}F_{opmi}\Lambda_{m0}\sin[iP_{opm}(\theta_s-\omega_o t)+\varphi_o]\\&\quad-\frac{1}{2}\sum_{i=1}^{\infty}\sum_{m=1}^{\infty}F_{opmi}\Lambda_{mm}\sin\left[(iP_{opm}+mN_m)\theta_s-iP_{ipm}\omega_o t+(\varphi_o+\varphi_m)\right]\\&\quad-\frac{1}{2}\sum_{i=1}^{\infty}\sum_{m=1}^{\infty}F_{opmi}\Lambda_{mm}\sin\left[(iP_{opm}-mN_m)\theta_s-iP_{ipm}\omega_o t+(\varphi_o-\varphi_m)\right]\end{aligned} \tag{4}$$

It can be seen from (4), the modulated magnetic field, ignoring the high order harmonics, produced by the outer rotor, that it is composed of two parts. The first part of the magnetic field generated by the MMF is the fundamental component of the permeance, and its pole pairs and rotation speed are equal to the outer rotor. The second part is the interaction between the MMF and the AC component of the permeance. The pole pairs number of the synthetic magnetic field is

$$P=\left|iP_{opm}\pm mN_m\right| \tag{5}$$

And the rotational speed of the synthetic magnetic field is

$$\omega=\frac{iP_{opm}\omega_o}{iP_{opm}\pm mN_m} \tag{6}$$

Similarly, after the inner rotor permanent magnets are modulated by the magnetic modulation ring, the synthetic magnetic field can be expressed as

$$\begin{aligned}B_{ipm}(\theta_s)&=F_{ipm}(\theta_s,t)\Lambda_s(\theta_s)\\&=\sum_{j=1}^{\infty}F_{ipmj}\sin[jP_{ipm}(\theta_s-\omega_i t)+\varphi_i]\\&\quad\times\left[\Lambda_{m0}-\sum_{m=1}^{\infty}\Lambda_{mm}\cos(mN_m\theta_s+\varphi_m)\right]\\&=\sum_{j=1}^{\infty}F_{ipmj}\Lambda_{s0}\sin[jP_{ipm}(\theta_s-\omega_i t)+\varphi_i]\\&\quad-\frac{1}{2}\sum_{j=1}^{\infty}\sum_{m=1}^{\infty}F_{ipmj}\Lambda_{mm}\sin\left[(jP_{ipm}+mN_m)\theta_s-jP_{ipm}\omega_i t+(\varphi_i+\varphi_m)\right]\\&\quad-\frac{1}{2}\sum_{j=1}^{\infty}\sum_{m=1}^{\infty}F_{ipmj}\Lambda_{mm}\sin\left[(jP_{ipm}-mN_m)\theta_s-jP_{ipm}\omega_i t+(\varphi_i-\varphi_m)\right]\end{aligned} \tag{7}$$

When the pole pairs and speed of the inner rotor satisfies

$$P_{ipm} = \left| P_{opm} \pm N_m \right|$$
$$\omega_i = \frac{P_{opm}\omega_0}{P_{opm} \pm N_m} \tag{8}$$

At this time, the pole pairs and speed of the modulated air-gap magnetic field of the outer rotor are equal to the inner rotor, which creates the stable magnetic coupling between the inner rotor and outer rotor and realizes the variable speed and variable torque transmission. The above is the essence of the magnetic field modulation principle.

When the principle of magnetic field modulation is applied to the electrical machine, each tooth of the stator and each salient pole of the rotor in the machine can be thought of as a modulation tooth, which changes the permeance of the air gap. The modulation tooth of stator and rotor can be considered respectively as

$$\Lambda_s(\theta_s) = \Lambda_{s0} - \sum_{m=1}^{\infty} \Lambda_{sm} \cos(mN_s\theta_s + \varphi_s)$$
$$\Lambda_r(\theta_r) = \Lambda_{r0} - \sum_{m=1}^{\infty} \Lambda_{rm} \cos[mN_r(\theta_r - \omega_r t) + \varphi_r] \tag{9}$$

where Λ_{s0}, Λ_{r0} are the fundamental amplitude of air gap permeance of stator and rotor, m are the harmonic orders, Λ_{sm}, Λ_{rm} is the amplitude of the m^{th} harmonics of air gap permeance, N_s, N_r is the tooth number, and φ_s, φ_r is the initial phase angle of permeance alternating component.

The MMF, generated by DC excitation or the permanent magnets in the machine, can be modulated by the modulation tooth. Different from the magnetic gear, the rotating magnetic field generated by the AC winding of the machine, which replaces the permanent magnet magnetic field of the outer rotor of the magnetic gear, interacts with modulated MMF to produce torque. In the latter part, the machine with various new topologies created by applying the magnetic field modulation principle will be introduced in detail.

III. Popular Topologies Based on Magnetic Field Modulation

In fact, many popular studies on the topological structure was not derived from the principle of magnetic field modulation at the beginning. After the magnetic field modulation principle was widely discussed, it was found that many machines had the shadow of the magnetic field modulation principle. These machines can be analyzed by the magnetic field modulation principle, which satisfies the three elements of the magnetic field modulation principle: excitation source, modulation unit (modulator), and AC winding.

A. Permanent Magnet Vernier Machine

Permanent magnet vernier machine (PMVM), as shown in Fig. 3, named because the small relative motion between stator and rotor will cause large change of air gap permeance, which similar to vernier caliper principle. The PMVM considers the stator tooth of the traditional permanent magnet machine as the modulation pole, and interacts between the rotating magnetic field generated by the stator winding of the low number of pole pairs and the modulated MMF of the rotor with the high number of pole pairs, resulting in large and low-speed torque.

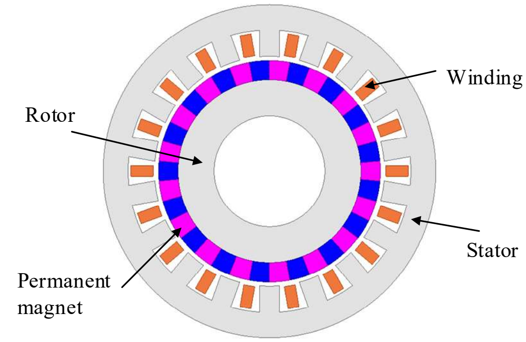

Fig. 3. The permanent magnet vernier machine (PMVM).

A PMVM having high torque at very low speed was proposed in direct drive systems for highly accurate position control of robots or factory automation machinery [10]. The stator has 30 pole pairs of permanent magnets, the rotor has 32 pole pairs of permanent magnets, and the stator winding is 2 pole pairs winding. The advantage of the PMVM is that it can be considered as combination of the traditional motor with the variable speed gear. The design of the machine has the embryonic form of the magnetic field modulation principle to some extent.

A. To and T. Lipo proposed surfacing PMVM[11]-[13]. The principle of torque generation is qualitatively analyzed. The large outer diameter of the rotor can increase the number of rotor poles so as to increase the torque density. In order to make full use of the machine space, a double-stator surface-mounted PMVM is proposed and tested, as shown in Fig. 4. Although the experimental results are different from the theoretical analysis, where the rated torque of the torque is about 11% lower than the designed value due to the higher iron loss and the mechanical loss, the torque density of the machine is still greatly improved.

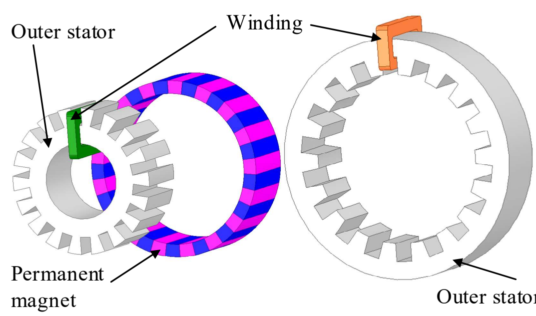

Fig. 4. The double-stator surface-mounted PMVM[11].

Besides, an outer-rotor PMVM, which can accommodate more pole pairs of permanent magnets, was proposed in [14], [15]. Which because the larger the air gap radius machine is, the higher the density of its torque. In [14], two new topological structures are proposed and compared. The proposed stator-PM PMVM can save the amount of permanent magnet, but the torque density is lower than the rotor surface-mounted permanent PMVM. The experiments proved that the PMVMs showed a relatively high torque density (Torque/effective volume) as 20 kNm/m^3 and 22 kNm/m^3, which is calculated through the data in the paper.

It can be seen that vernier machines have huge advantages in design, manufacturing, control, performance, reliability, etc. However, VMPMs are suffering from lower power factor which need auxiliary equipment in practical application. If the power factor can be improved by machine design, PMVMs would be a better candidator in more applications.

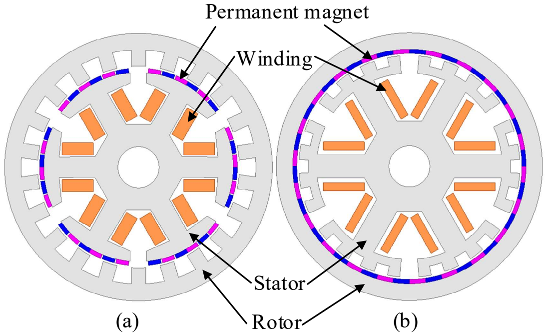

Fig. 5. The outer-rotor PMVM[14]. (a) Stator PM machine. (b) Rotor PM machine.

In addition, the function and influence of fractional slot concentrated winding (FSCW) in the PMVM are analyzed in [16]-[18]. Higher performance can be obtained by adjusting the slot ratio. Because its fractional slot winding can increase the difference of pole pairs between stator and rotor, FCSW can also reduce copper losses due to its shorter winding ends.

B. Flux Reversal Machine

The basic topology of the flux reverse permanent magnet machine is shown in Fig. 6. This topology has a double salient structure similar to the reluctance machine, but a pair of permanent magnets are placed on each stator tooth. The flux reverse machine can be traced back to [19] in 1997. However, this structure has a certain magnetic flux leakage, which reduces the torque density to some extent. The flux, generated by a pair of permanent magnets on a tooth of the flux reversal machine (FRM), is closed in the stator tooth and across the tooth, respectively, which generates variable flux linkage. Like a permanent magnet machine, the FRM works on the principle of variable flux linkage, which can induce EMF by interacting with stator winding current.

In order to improve the torque density of the machine, a series of new topologies based on FRM are constantly emerging in subsequent studies. In [20], [21], more permanent magnets are placed on a stator tooth to improve the performance of the FRM. The results show that the new topology FRPM has better magnetic circuit distribution, larger flux linkage, and back electromotive force (EMF). And in [22], the influence of the magnetization direction of the stator permanent magnet of the FRM is discussed. The magnetization direction of a permanent magnet can be divided into two types: the same and the opposite direction of the adjacent permanent magnet on both sides of a stator slot. In [22], the torque density of FRMs are about 7.2 kNm/m^3 (calculated) by a current density of 5 A/mm^2. Compared with PMVMs, the FRMs have higher speed and lower torque density in the same efficiency.

Later, Z. Zhu studied the effect of permanent magnet arrangement on the performance of FRM[23], including the

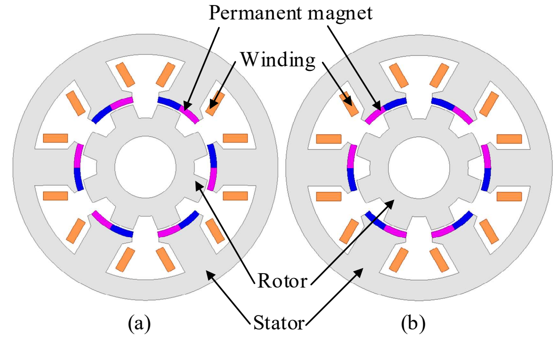

Fig. 6. The flux reverse machine (FRM).

stator tooth containing more permanent magnets, as shown in Fig. 7. At the same time, Z. Zhu used the magnetic field modulation principle to analyze the FRM and completely explains the causes of the FRM's torque generation from the magnetic field modulation principle's perspective. The research shows that the torque density of the tooth with four permanent magnets on each tooth is higher than that of the tooth with two permanent magnets. And the machine with the opposite polarity of the adjacent permanent magnets in the slot has the highest torque density and efficiency. And the highest torque density of the above FRM is 14.5 kNm/m^3 (calculated), almost twice as high as before.

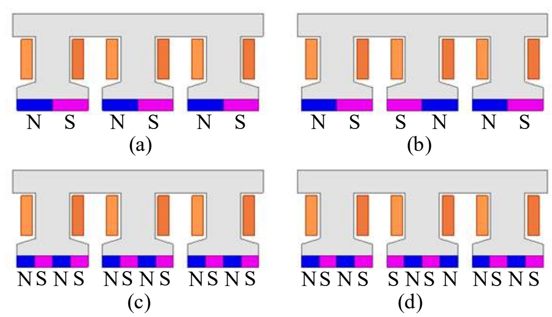

Fig. 7. The different permanent magnet arrangements[23]. (a) NSNS. (b) NSSN. (c) NSNS-NSNS. (d) NSNS-SNSN.

Based on the above structure of FRM, T. H. Kim proposed an internal FRM[24]. This FRM embed the surface-mounted permanent magnet (SPM) into the stator tooth so as to reduce the flux leakage and improve the performance of the machine. In contrast to the traditional FRM, the magnetization direction of the internal FRM permanent magnets is circumferential. The permanent magnet is parallel to the stator flux linkage, so it is more difficult to demagnetize. The iron consumption[25] and demagnetization[26] situations of internal FRM are then investigated. This internal FRM improved the torque density but reduced mechanical strength.

In addition, a consequent pole flux reversal machine (CPFRM) is proposed to reduce the permanent magnet consumption[27]. The CPFRM replaces one of a pair of permanent magnets in each tooth with an iron tooth, which is similar to the consequent pole rotor. The CPFRM topology reduces the leakage of stator permanent magnets, improves the torque density, back EMF, and overload capacity.

In [28], the CPFRMs with different stator permanent magnet topologies are analyzed and compared. The magnetic field

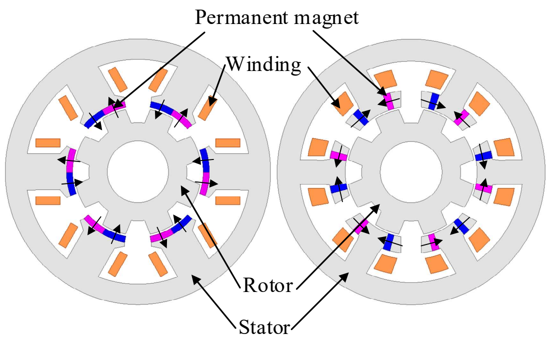

Fig. 8. The internal flux reversal machine[24].

modulation principle is used to analyze how the MMF of the permanent magnet is modulated and the harmonic composition of the air gap magnetic field. The torque of CPFRM is analyzed to determine which harmonics of the air gap magnetic field can interact with the stator winding. And in [29], [30], further, the slot/pole matching of CPFRM is analyzed, which optimizes the structure topology and improves the torque density. And the CPFRM in Fig. 9 (d) has the highest toque density of 17.6 kNm/m^3 (calculated), which saves almost half of PM materials.

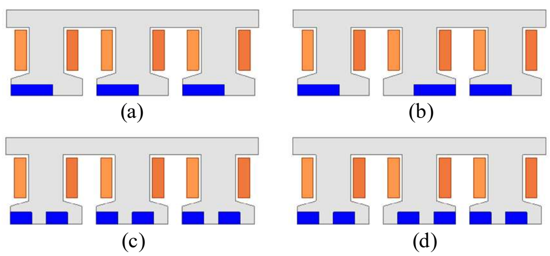

Fig. 9. Different CPFRM topologies. (a) N/Fe-Fe/N. (b) N/Fe-N/Fe. (c) N/Fe/N/Fe-Fe/N/Fe/N. (d) N/Fe/N/Fe-N/Fe/N/Fe.

C. Flux Switching Machine

The flux switching machine (FSM) is similar to the FRM. The stator and rotor have a double salient pole structure. In the FSM, the stator teeth are separated into U-shaped cores, and the radial magnetized permanent magnets are placed between the U-shaped cores. The rotor of FSM is a salient pole rotor without a permanent magnet, and the topology rotor also has a simple structure and strong robustness. Although different from the topology of FRM, FSM has the same working principle and rotor structure characteristics as FRM, which can be regarded as evolved from FRM, as shown in Fig. 10.

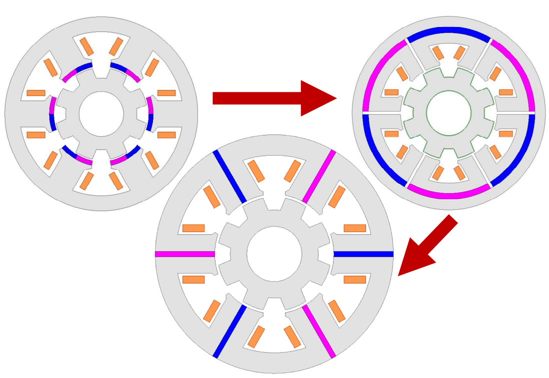

Fig. 10. From flux reversal machine to flux switching machine.

The FSM can be traced back to 1955, when they proposed the Single-Phase Flux Switching AC Generator[31]. Later, E. Hong completely proposed a three-phase FSM of the 12 slots and 10 poles, however, which had not shown interesting performances[32]. Since then, the FSM has been widely studied[33]-[36].

With the attention caused by FSM, the hybrid excitation FSM has begun to be proposed[37], [38]. This topology added DC winding to the stator, thereby increasing the torque density to 15.7 kNm/m^3 (calculated) and magnetic regulating ability of the FSM. The experiment proved that this topology has a smaller loss. However, this stator of FSM is relatively complex and difficult to manufacture.

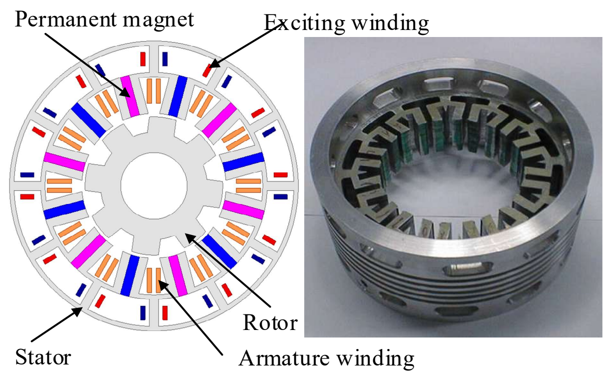

Fig. 11. The hybrid excitation FSM[37], [38].

A novel hybrid excitation FSM topology was also suggested in [39]. This topology creates a flux bridge on the stator's excitation winding to increase the excitation coil's efficiency and raise the machine's torque density. To improve the performance of the machine, a straightforward lumped-parameter magnetic circuit model is created. The stator and its winding are difficult to construct, even though the rotor of this topology has a straightforward structure.

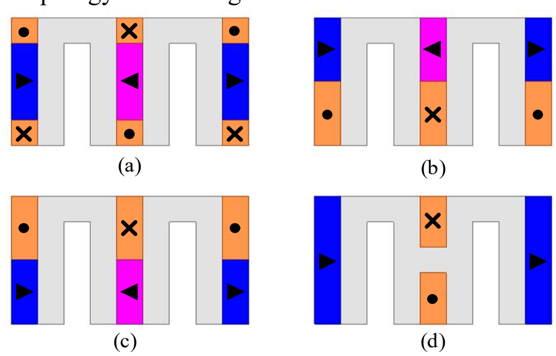

Fig. 12. Schematic view of the magnet and field coil arrangements for four hybrid FSM machines[38].

With the proposing of various structural topologies, scholars have discovered the magnetic field modulation effect in these machines. Professor Z. Zhu analyzed the principle of magnetic field modulation in FSM. In [40], the MMF generated by the magnetic source, the modulation effect of the rotor salient pole, and the analysis in harmonic of the air gap magnetic field are theoretically derived, and the slot pole combination is analyzed, which indicates that the modulation effect of the rotor salient pole in magnetic field modulation on PM in FSM and the reaction field between excitation winding and armature is essentially the same as that in magnetic gear.

Later in [41], the operation principle of FSM is systematically and detailedly discussed from the perspective of the magnetic field modulation principle. The traditional FSM often does not know why the back EMF is a sine wave when explaining its operation principle. Now, the modulation process of a flux-switching machine is analyzed in detail, the modulation function of FSM and the distribution function of air gap magnetic field are deduced, the generation principle of FSM back EMF is explained, and the analytical model is established. And in the subsequent research, the composition of FSM electromagnetic torque is given, which provides theoretical support for the subsequent analysis of FSM and the research of new topologies[42].

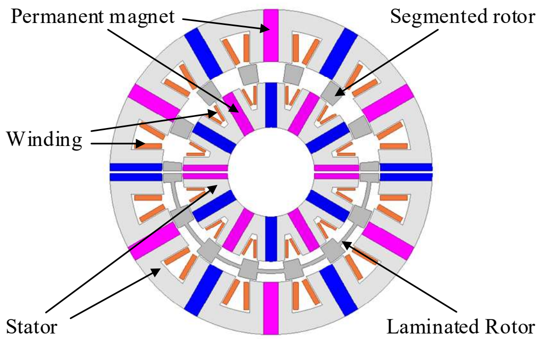

Fig. 13. The counter-rotating double-sided flux switching permanent magnet machine[43].

Based on the principle of magnetic field modulation, the Counter-Rotating Double-Sided Flux Switching Permanent Magnet Generator is studied[43], [44].The principle of FSM is studied, and the magnetic equivalent circuit model is built by comparing it to a segmented rotor without a yoke and a laminated rotor with the salient pole. The test confirmed that the machine's torque density had improved to some extent.

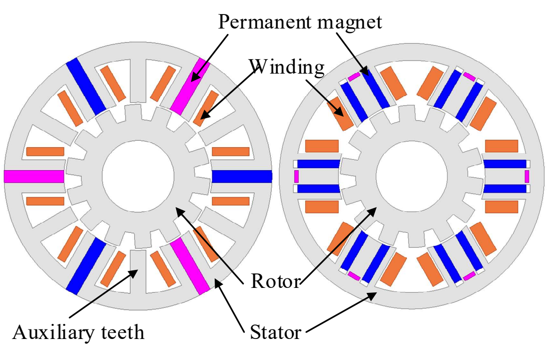

Fig. 14. The consequent pole flux-switching machine[45].

Additionally, a novel consequent pole flux-switching machine (CPFSM) with a stator yoke bridge is proposed based on the same idea of magnetic field modulation[45]. By strengthening the low-order air gap magnetic field, the iron bridge design in the stator yoke increases the machine stator's structural strength and boosts torque density.

IV. Magnetic Field Modulated Dual Permanent Magnet Machine

In earlier investigations, there have been numerous stator/rotor dual permanent magnet (DPM) structures[46]-[50]. This type of DPM machine primarily takes advantage of the air-gap magnetic field's pole number, which is produced by modulating the permanent magnets in the rotor and stator by their respective salient poles and teeth in order to improve the torque density of the machine. In [46], the dual PM machines with various structures are compared and analyzed, including stator multitooth-PM machine[46], [47], stator tooth-PM machine[48] and stator slot-PM machine[49].

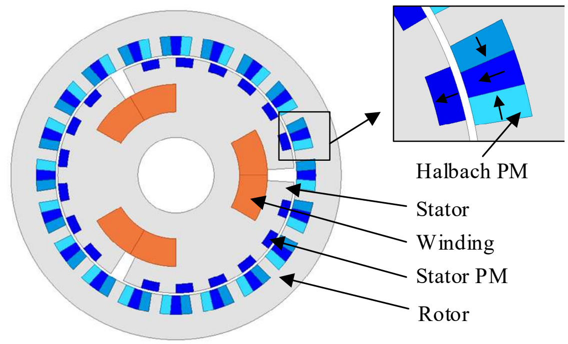

Fig. 15. The DPM machine with stator multitooth-PM[46].

In [51], the air gap magnetic field modulation principle and the characteristics of FCSW are analyzed in detail, and the two are linked. The paper shows that some traditional (SPM) machines also have the phenomenon of magnetic field modulation, which is also the reason for the large torque density of these kinds of permanent magnet machines. It can be seen as a combination of traditional (SPM) machines and PMVMs.

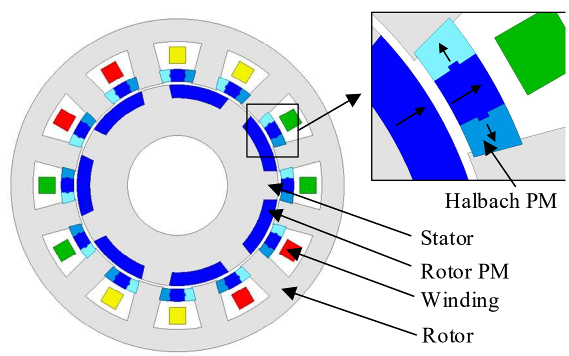

Fig. 16. The DPM with stator slot-PM[52].

On this basis, a new slot-pole matching dual permanent magnet machine based on the magnetic field modulation principle is proposed[52]. The machine uses the rotating magnetic field generated by FCSW to interact with both the fundamental magnetic field of the rotor permanent magnet and the harmonic magnetic field of the stator and rotor permanent magnet after modulation, which improves the torque density of the machine.

In [53], [54], a new type of dual-permanent magnet dual-winding machine is proposed, which makes full use of the rotor space and opens deeper slots in the rotor space to place permanent magnets. The machine can be seen as a combination of two permanent magnet machines, but the torque is not just a simple sum of the two machines' torque. Based on the principle of magnetic field modulation, four torque components can be produced by the interaction between the stator and rotor permanent magnet and stator/rotor AC winding.

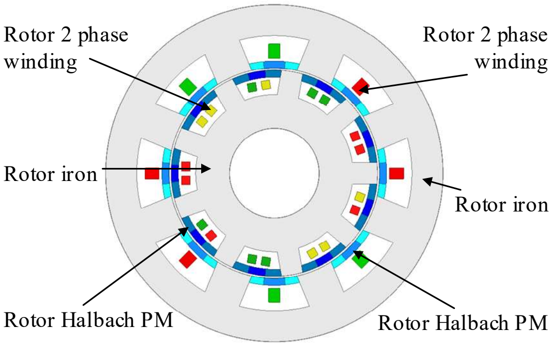

Fig. 17. The dual-permanent magnet dual-winding machine[53].

V. Magnetic Field Modulated DC Biased Machine

With the advent of ways to make full use of the large number of harmonics in FSCW to enhance power density, various multi-source topologies have been proposed. The so-called "multi-magnetic source" refers to the increase of machine torque density by multiple permanent magnets and DC excitation. This multi-source topology can not only improve the torque density of the machine, but also greatly improve the redundancy and fault tolerance of the machine. When a magnetic source fails, the machine can continue to operate through other magnetic sources. The machine can add DC excitation to the stator to provide excitation MMF in the air gap to form hybrid excitation. However, the additional DC excitation winding in the stator will occupy the slot space to reduce the AC current density. A DC biased winding can be formed by combining DC excitation with AC winding. Compared with the machine with DC winding alone, although this winding also reduces the AC component at a constant total current density, it is generally higher than that with DC winding alone. A DC biased winding current can be expressed as

$$\begin{aligned} i_A &= \sqrt{2}I_{\mathrm{ac}}\sin\left(\omega_e t+\alpha\right)+I_{\mathrm{dc}} \\ i_B &= \sqrt{2}I_{\mathrm{ac}}\sin\left(\omega_e t+\alpha-2\pi/3\right)+I_{\mathrm{dc}} \\ i_C &= \sqrt{2}I_{\mathrm{ac}}\sin\left(\omega_e t+\alpha+2\pi/3\right)+I_{\mathrm{dc}} \end{aligned} \tag{10}$$

where I_{dc} the amplitude of dc component, I_{ac} the amplitude of ac component, and ω_e is the electrical angular velocity.

Some DC biased PMVMs are proposed in[55]-[59]. The working principle of the machine is similar to that of the stator PMVM. The DC component in the winding can produce a MMF similar to that of the permanent magnet. The MMF can be modulated by the rotor salient pole. After modulation, it acts with the AC component of the winding to produce additional torque. And in [60] the topologies of different slot pole combination are analyzed and comprised.

In[61], [62], a DC-biased stator PMVM is proposed. Based on the reluctance vernier machine, the machine adds two magnetic sources of permanent magnet and DC excitation, and all the magnetic sources are concentrated on the stator, so that the machine has a rotor with a simple structure and high reliability, and the stability of the machine is improved, and the torque density improves to 25.5 kNm/m^3 (calculated). This paper explains how the machine uses the magnetic field modulation principle to improve the torque output, and analyzes its slot-pole combination.

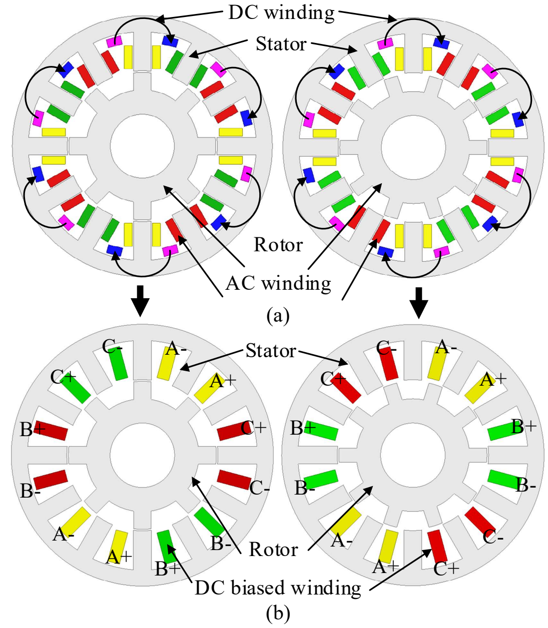

Fig. 18. The DC biased PMVMs[55].

In order to further improve the torque density of the machine, a new DC biased DPM machine was proposed in [63]. The stator of the machine adopts the separated tooth structure, and the permanent magnet is placed on the stator tooth. Both the rotor and the stator are consequent pole structures. The stator winding is DC biased FSCW. The machine has a total of three magnetic sources, which are modulated by the stator tooth and the rotor salient pole, respectively, and then act on the AC rotating magnetic field to generate torque. In this paper, the slot pole cooperation of this topology is compared and analyzed, and the proportion of DC component in DC biased current is analyzed to obtain the optimal torque output. Finally, the highest torque density is about 28.3 kNm/m^3. Theoretically, considerable torque output can be superimposed, but the saturation effect of ferromagnetic materials limits the improvement of torque to some extent.

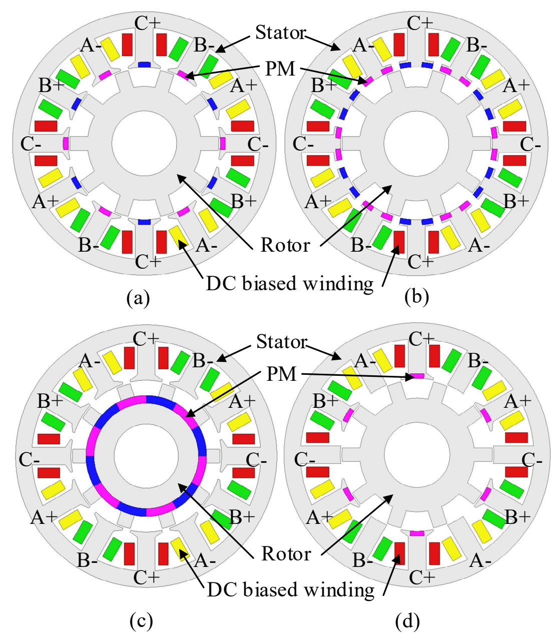

Fig. 19. Four type topologies of the DC biased PMVM[61].

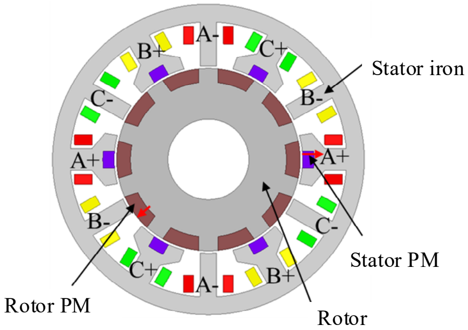

Fig. 20. The DC biased DPM machine[63].

VI. Conclusion

After summarizing and analyzing the research results in the literature, in fact, the topological structure of many popular studies on motors was not derived from the magnetic field modulation principle when it first appeared. It can be found that the proposal of magnetic gear and the combination with motor makes a number of new topologies emerge. Furthermore, after the emergence of the principle of magnetic field modulation, the motor has been analyzed from a new perspective, and derived a large number of motor topologies with higher torque density and better performance, which has glowed new vitality for the whole motor field. And many scholars used the principle of magnetic field modulation to propose many new high torque density motor topologies. In the study of high -power density in the future, the principle of magnetic field modulation will play a more important role.

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