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Overview of Permanent Magnet Wind Power Generators

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With the advancement of renewable energy technologies and the increasing emphasis on environmental issues, wind power generation systems have experienced rapid development. Permanent-magnet (PM) machines have been widely favored in the generator domain due to their high torque density, high reliability, and high efficiency. This article provides a detailed review of PM machines applied in wind power generation systems, categorizing the types of machines based on the number of mechanical and electrical ports. The paper emphasizes the generator topologies, operational principles, and performance characteristics, while also comparing the advantages and disadvantages of different structures. Furthermore, this article discusses the current challenges faced by PM wind generators and outlines future development trends.

***Index Terms*—Electrical port, hybrid excited, mechanical port, permanent magnet generator, wind power generation.**

I. Introduction

The global shift to renewable energy is driven by concerns over energy security and environmental pollution, especially in the face of climate change and dwindling fossil fuel resources. Wind energy, which produces minimal pollutants and significantly reduces greenhouse gas emissions, is emerging as a key solution. As demand for clean energy grows, wind power is expected to play a larger role in combating climate change and ensuring energy security, having already become a major source of clean electricity. [1][2].

The development of wind power generation systems must be accompanied by the continuous progress of wind power generator. Historically, wind power generation systems predominantly employed non-permanent magnet (PM) machines, notably squirrel cage induction generators (SCIGs). Although SCIGs are valued for their robustness and low initial cost [3], they present significant downsides, including high starting currents and diminished power factors, which can adversely affect grid stability and energy efficiency, even though these problems can be solved by some power electronic devices [4][5]. To mitigate these issues, the development of wound rotor induction generators (WRIGs) and electrically excited synchronous generators (EESGs) marked a pivotal point. WRIGs utilize rotor windings coupled with external resistors to enhance starting characteristics, the speed of the rotor magnetic field can be kept synchronized with the speed of the stator by adjusting the external equipment [6]-[9]. The EESG generates an exciting magnetic field through an additional excitation system, which then interacts with the rotating magnetic field of the armature to generate a torque. However, both technologies are based on brushed slip rings, which introduce maintenance challenges and reliability concerns. The novel brushless electrically excited synchronous generator eliminates the influence of the slip ring and brush [10]-[12], but it still needs to consume additional energy to generate the excitation field.

The increasing focus on enhancing the reliability and efficiency of wind power systems has fostered interest in PM technology [13][14]. PM generators operate brushlessly, removing the need for brushes and slip rings, which lowers maintenance and enhances reliability. PMs directly supply the magnetic field, reducing extra excitation energy use. PM wind generators benefit from compactness, high efficiency, power density, and broad operational range. [15]-[18].

In general, conventional electrical machines contain an electrical port (EP) and a mechanical port (MP), also called single electrical port (SEP) and single mechanical port (SMP). The EP is responsible for the input/output (I/O) of voltage and current, and the MP is responsible for the I/O of torque and speed [19]. Dual mechanical ports (DMP) represent the

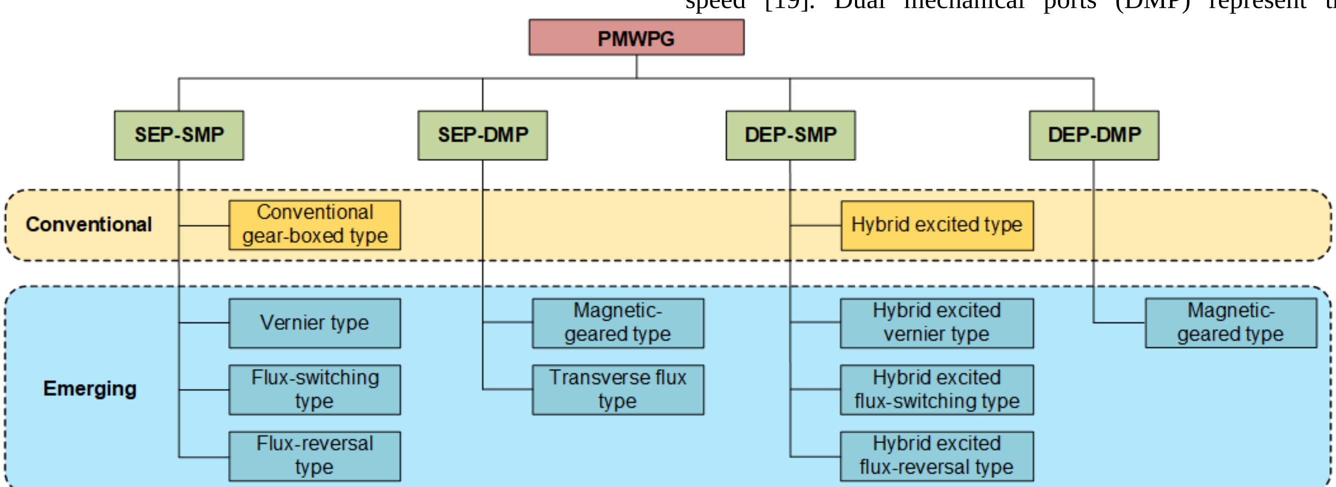

Fig. 1. Classification of PMWPGs.

machine with two rotating parts, and dual electronic ports (DEP) usually represent the machine with two sets of armature windings. Dual-port machines have developed rapidly in the field of electrical machines in recent years [20].

The existing electrical machine technologies can be flexibly integrated with other machine types through different configurations and connection methods, allowing for a dynamic interchange among various mechanical and electrical port structures rather than being confined to a fixed number of ports, as for example the Pseudo-Direct Permanent Magnet Drives (PDD). In order to give a comprehensive review of the existing academic field of PM wind power generators (PMWPGs) topologies and other PM machine topologies can be applied to wind power generation, this paper sorts PMWPGs by the number of EP and MP. According to the number of electrical and mechanical ports and combining them, PMWSGs can be divided into four categories, SEP-SMP PMWPGs, SEP-DMP PMWPGs, DEP-SMP PMWPGs, DEP-DMP PMWPGs, as shown in Fig. 1, which including the representative types.

This paper is organized as follows. Sections II and III deal with the SEP-SMP and SEP-DMP machine respectively. DEP-SMP and DEP-DMP machines are discussed in Sections IV and V respectively. Section VI described the challenges and future development trends of PM machines. Section VII is the conclusion part.

II. SEP-SMP PMWPGs

SEP-SMP machine represents the most common machine configuration. This type of machine features one EP and one MP. The EP is responsible for the I/O of electrical power, which can be supplied through either single-phase or three-phase power. The MP is responsible for the I/O of mechanical energy, typically connected to the rotor of the machine.

A. *Conventional Gear-boxed Type*

The development of PM machine began in the 19th century, primarily relying on natural magnets and basic electromagnetic principles. With the advancement of PM materials, the performance of PM machine has continuously improved. PM machines used in wind power generation are typically PM synchronous machines (PMSM), as shown in Fig. 2, also known as PM brushless AC machines (BLACM) [14].

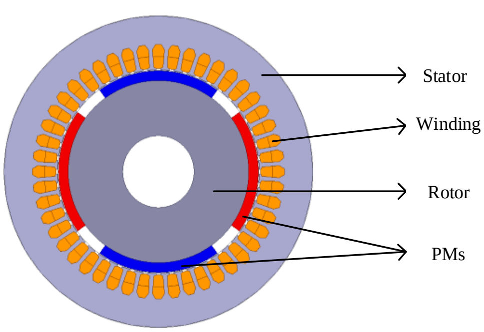

Fig. 2. Typical PMSM.

The stator core is usually made of silicon steel sheets to reduce iron losses. PM materials can be surface mounted on the rotor or embedded within the rotor. The rotor is connected to the blades through a gearbox. The transmission through gears will reduce the overall efficiency of the system, hence, the direct drive generator suitable for wind power generation is gradually emerging.

B. *Vernier Type*

The development of the permanent magnet vernier machine (PMVM) can be traced back to the 1980s, the emergence of PM materials has accelerated the combination and development of PMs and vernier machines [21]. The PMVM has consistently garnered attention due to its simple structure and high torque density. A typical PMVM is depicted in Fig. 3(a). PMVM's high torque benefits from flux modulation principle, which is also known as magnetic gearing effect [23]. Moreover, when the number of rotor pole pair (p_r), the number of stator slots (Z) and the number of winding pole pair (p_w) meet a certain relationship, the torque can reach the maximum value. The relationship is as follows:

$$p_r = |Z - p_w| \tag{1}$$

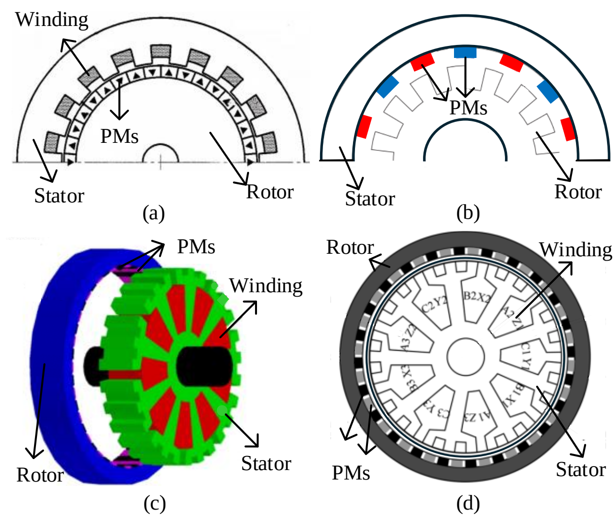

Fig. 3. Vernier PM machines. (a) Typical PMVM [22]. (b) Outer-rotor PMVM [25]. (c) Outer-rotor PMVM with toothed-pole stator [26]. (d) HTS PMVM [29].

PMVM structures usually contain a relatively small number of stator slots and a large number of rotor poles in order to achieve better results [24], this structure makes the rotor after a small angle rotation, in the stator winding can produce a larger magnet flux, the whole system can produce a greater torque at low speed, low speed and high torque is also the main advantage of PMVM.

Outer-rotor machines offer better heat dissipation than inner-rotor types and are easier to assemble due to being connected to the wind blade directly, making them ideal for direct-drive wind power applications.

In [25], Zhang et al. presented a high performance outer-rotor PMVM, as shown in Fig. 3(b). In [26], Li et al. presented an outer-rotor PMVM for wind power generation, as shown in Fig. 3(c), which introduces the idea of flux-modulation poles (FMP) and the FMP is just the tooth in the outer part of the inner stator. This structure can capture the wind at low speed and generate a high-speed rotating field to improve the power density. In [27], Liu et al. presented a novel fault-tolerant PMVM (FTPMVM), which incorporates the merits of high torque and high fault tolerance by adding fault-tolerant tooth to the stator surface, the basic principle is similar to that in [26]. In [28], Xu et al. make an improvement to FTPMVM in [27], the Halbach array is arranged to further improve the torque density, achieve a higher power factor, and can reduce losses. These are significant factors related to wind power generation. A bold idea was put on display in [29] which combines the high-temperature superconductor (HTS) with PMVM, as shown in Fig. 3(d). The design features a streamlined structure comprising a single layer of air gap, while the utilization of HTS materials facilitate rapid cooling, thereby significantly enhancing the efficiency of the power generation system.

C. Flux-switching Type

Conventional PM machines typically have the PMs located on the rotor, as seen in surface-mounted PM machines and inserted PM machines. Flux-switching PM machines (FSPMM), however, position PMs on the stator, improving performance. FSPMMs are notable for high torque, heat dissipation, and reliability, gaining attention in recent years. The modern three-phase FSPMM was first introduced by Hoang et al. in 1997 [30].

Fig. 4 illustrates the operating principle of FSPMM which is focused on the "generator-oriented" perspective [31]. As shown in Fig. 4, coil X is an arbitrary coil. When the rotor is at position A, the magnetic circuit reluctance becomes the minimum as the rotor teeth are aligned with the stator teeth. The flux-linkage of coil X is at its maximum value. The magnetic circuit reluctance becomes the maximum as the rotor teeth are aligned with the stator slots when the rotor rotates to position B and no magnetic flux lines go through coil X at this point. When the rotor rotates to position C, the magnetic circuit reluctance becomes the minimum and the flux-linkage reaches its maximum value again, which is similar to the scenario at position A, but its polarity is reversed. Finally, when the rotor rotates to position D, it becomes the same situation as location B.

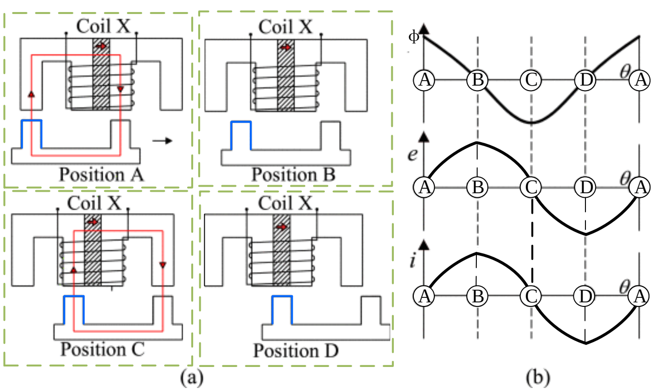

Fig. 4. Principle of FSPMM from generator-oriented perspective [31]. (a) Rotor at four typical positions. (b) Ideal flux-linkage, back-EMF, and phase current waveforms versus rotor angular position.

A typical topology of an FSPMM is illustrated in Fig. 5(a) [30]. As shown, the PMs are positioned within the stator and are surrounded by a concentrated winding with fractional slots, while the PMs are also complemented by the U-shaped teeth of the stator, resulting in a simple overall structure. Furthermore, the placement of PMs on the stator effectively addresses heat dissipation issues [32].

In [33], Ojeda et al. presented small-scale FSPM wind power generator with 120 stator teeth and 100 rotor teeth, as shown in Fig. 5(b), these small-scale wind power generators are well-suited for deployment in limited areas, such as rural regions and farms. Direct-drive FSPMM represents a highly competitive option for small-scale wind power generators.

Fault tolerance is crucial for machine performance, ensuring operation after faults. In [34]-[36], Zhao et al. improved fault tolerance in three-phase FSPMMs, especially for open and short-circuit winding faults, Fig.5 (c) shows the topology in [34]. In [37], Li et al. presented a nine-phase FSPM machine for wind power generation. The paper presents three topologies with different stator/rotor-pole combinations, 18/16, 18/17 and 36/34, Fig.5 (d) shows the topology and prototype of 36/34 stator/rotor-pole in [37]. It shows that the cogging torque of 18/17 and 36/34 machines can almost be neglected compared to 18/16, the 18/17 machine has the highest PM utilization.

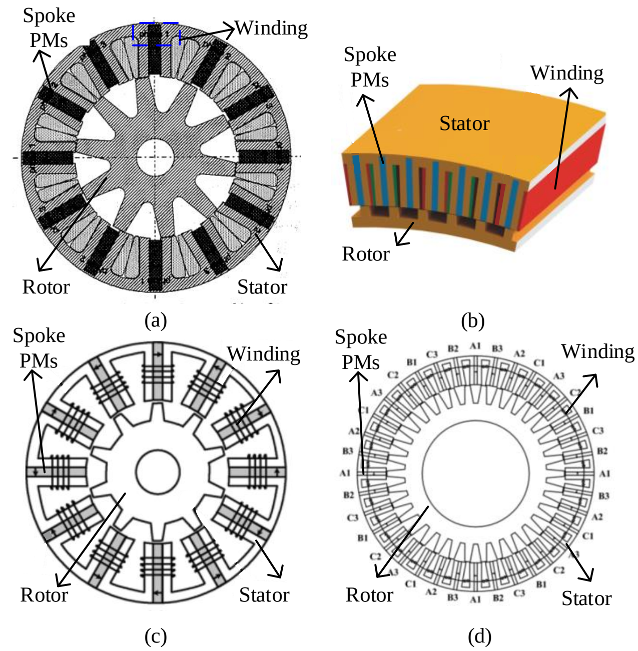

Fig. 5. Flux-switching spoke PMs machines. (a) Typical FSPM machine [30]. (b) 120/100 FSPM machine [33]. (c) FSPM machine with high fault tolerance [34]. (d) 36/34 FSPM machine [37].

D. Flux-reversal Type

Flux-reversal PM (FRPM) machines have received a lot of attention in the past few years. These machines are usually simple in structure, can respond quickly and have high power density and low inertia, essentially similar to the brushless doubly salient PM machines [38]. A typical FRPM machine topology is shown in Fig. 6(a). As can be seen, A series of PMs are mounted on the inner surface of the stator teeth in an alternating configuration. The windings are directly wound around the stator teeth. When the rotor rotates, the area of the two PM segments that directly face each stator tooth changes depending on the rotor's position. This variation leads to fluctuations in the magnetic flux and back EMF waveforms within the bipolar winding of the stator teeth.

In [39], Boldea et al. introduced a FRPM for low-speed drive, as shown in Fig. 6(b). In [40], More et al. presented a 6/14 stator/rotor pole FRPM machine for direct-drive-rooftop wind power generation, as shown in Fig. 6(c). In [41], More et al. compared the machine in [40] with conventional PMSM, under the premise of the same structure configuration. It was found that the power density of compensated 6/14 pole FRPM is approximately 1.5 times that of 28 pole PMSM, and the FRPM has better constant power speed range. In [42], K. T. et al. presents a novel 3-phase 12/8-pole FRPM machine for wind power generation, which exhibits higher efficiency, power density and reliability compared to conventional switched reluctance (SR) and induction machine for wind power generation, as shown in Fig. 6(d). In [43], Li et al. also introduced a 6/14 pole FRPM, as shown in Fig. 6(e), the PMs are mounted on the surface of each stator teeth. A FRPM with evenly distributed PMs was proposed by Li et al. in [44], as shown in Fig. 6(f), this machine exhibits 33% higher average torque, 78% lower cogging torque, and 72% lower torque ripple.

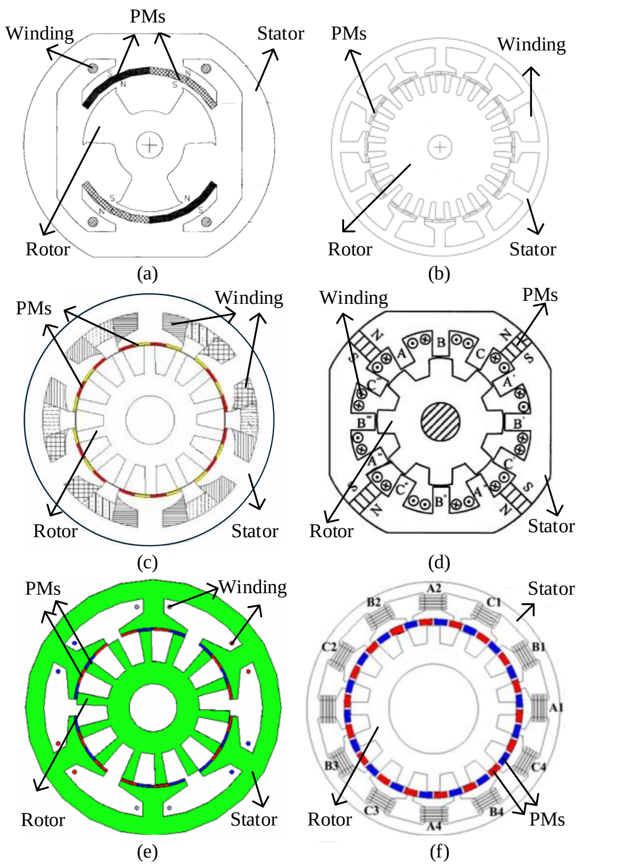

Fig. 6. Flux-reversal PM machines. (a) Typical FRPM machine [38]. (b) Low-speed FRPM machine [39]. (c) 6/14 FRPM machine [40]. (d) 3-phase 12/8-pole FRPM machine [42]. (e) FRPM with mounted PMs [43]. (f) FRPM with evenly distributed PMs [44].

III. SEP-DMP PMWPGs

SEP-DMP PMWPGs typically comprise an EP connected to the windings, responsible for the I/O of electrical energy. Additionally, they contain two MPs, one is connected to the turbine blades, while another is usually equipped with pole pieces that modulate magnetic flux. Depending on the design, the rotor may be positioned either within the stator or encircle the stator externally.

A. *Magnetic-geared Type*

Traditional magnetic gear systems reduce wear and maintenance compared to mechanical gears but have lower torque density and complex circuits [45]. Rare-earth PMs with magnetic gearing enhance torque density and power factor, benefiting wind power applications. Fig. 7(a) shows the topology of magnetic gear. It is found that the machine combines two rotors connected with I/O shaft, which causes the machine to own two MPs. The torque is produced between the inner rotor and outer rotor based on modulation of magnetic fields produced by two PM rotors [46]. The rotating ferromagnetic pole pieces plays a key role in flux modulation, which modulated the same number of poles and same speed for stator and rotor. Therefore, a stable torque output is generated and can achieve the effect of low speed and high torque, which is very suitable for wind power generation.

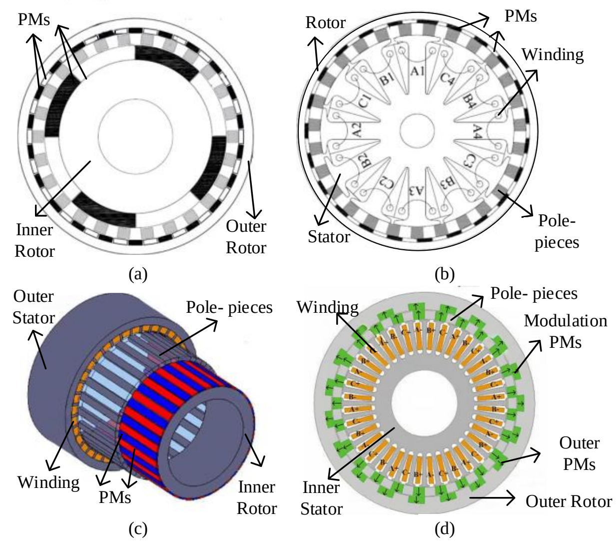

Fig. 7. Magnetic-geared PM machines. (a) Magnetic gear [47]. (b) Typical MGPM machine [47]. (c) Inner rotor MGPM machine [50]. (d) Dual-layer MGPM machine [51].

In [47]-[49], the most fundamental form of the magnetic gear combined with the PM machine is introduced, which is also the structure of the magnetic gear originally introduced into the PM machine through the form of the outer rotor, as shown in Fig. 7(b). The outer rotor is directly coupled to the wind blade, and the magnetic gear allows the generator to operate at high speed, which can capture wind energy more efficiently and improve power density. The overall system is attractive enough for wind power generation. In [50], Crider et al. proposed an inner MGPM generator, as shown in Fig. 7(c), it was found that its efficiency is higher than conventional PMSM.

Wang et al. [51] presented a dual-layer MGPM with dual flux modulating effect, as shown in Fig. 7(d). Differing from the conventional MGPM machine, almost the same number of PMs are arranged in the modulation segments and the rotor, and the magnetization direction is the same. The modulation segments can also be utilized as inner rotor to let the machine run, which also means that both the outer rotor and the inner rotor can utilize the windings for energy conversion. Therefore, high efficiency and high torque density are achieved, which are key factors for wind power generation. In [52], Zhang et al. proposed a MGPM machine in which the rotor and the modulation segments are enclosed in the stator, the same effect as [51] is achieved through dual flux modulating effect.

B. *Transverse Flux Type*

The concept of the transverse flux machine (TFM) was first introduced by Morday in 1885 [53]. One of the primary advantages of TFM is the decoupling of the spatial requirements for the stator teeth and armature conductors. This allows the magnetic and electrical loads to be independently configured, enabling higher torque density [54].

Extensive research has been conducted on the application of TFM in wind power generation. In [55], Husain et al. presented a double-sided TFM for direct-drive wind turbine applications, the rotor utilized a magnetic flux concentration setup which produces the high airgap magnet flux. In [56], Weh. et al. presented a double-side TFM for generation. However, TFMS with DEP have rarely been researched. In [57], Jiang et al. presented a dual-rotor TFPM machine, as shown in Fig. 8(a). Compared with conventional TFM which is shown in Fig. 8(b), the novel model with PM positioned within the dual-rotor structure, is capable of modulating and generating a high-frequency air-gap magnetic field even at low relative rotational speeds based on flux modulation effect. Moreover, designing the stator in a C-shape can reduce magnetic leakage and manufacturing complexity.

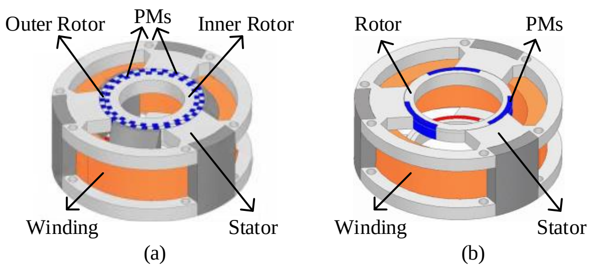

Fig. 8. Transverse flux PM machines [57]. (a) Dual-rotor TFPM machine. (b) Conventional TFPM machine.

IV. DEP-SMP PMWPGS

Hybrid excitation is seen in typical DEP machines, which improves PM machine efficiency and adjustability. In DEP-SMP types, two EPs connect to armature and excitation windings, enabling the I/O of electrical energy and excitation current. The MP remains connected to the wind turbine blades.

A. *Hybrid Excited Type*

The hybrid excited synchronous machine (HESM) was first introduced in the 1980s, which combines PM and excitation windings to provide rotor magnetomotive force (MMF). The PMs maintain steady magnetic flux, while excitation windings regulate flux distribution. The HESMs achieve high torque at low speeds, a broad speed range, and efficient operation with proper control. [58]-[60].

In [61], Luo et al. presents the HESM structure which PM and excitation coils located in the rotor, as shown in Fig. 9(a), the number of rotor pole can vary by adjusting the excitation current. There are two magnetic flux paths associated with each PM: one runs through the adjacent magnetic pole, while the other traverses through the nearby excited pole. In [62], the PM and excitation coils of HESM located in the stator, as shown as Fig. 9(b), which is found that PMs and the excitation coils do not make contact, and the stator and rotor possess different pole numbers.

In [63], Liu et al. present a dual-stator HESM for wind power generation, as shown in Fig. 9(c), which is found that the power density and the output voltage can be effectively increased by adopting a dual-stator structure. In [64], Tapia et al. presented the HESM which PMs in the rotor and excitation coils in the stator, as shown in Fig. 9(d). Liang et al. analyzed a consequent-pole HESM which is applicable for constant voltage power generation in [66]. In [67], Naoe et al. presented a HESM that both the PMs and excitation coils on the same shaft.

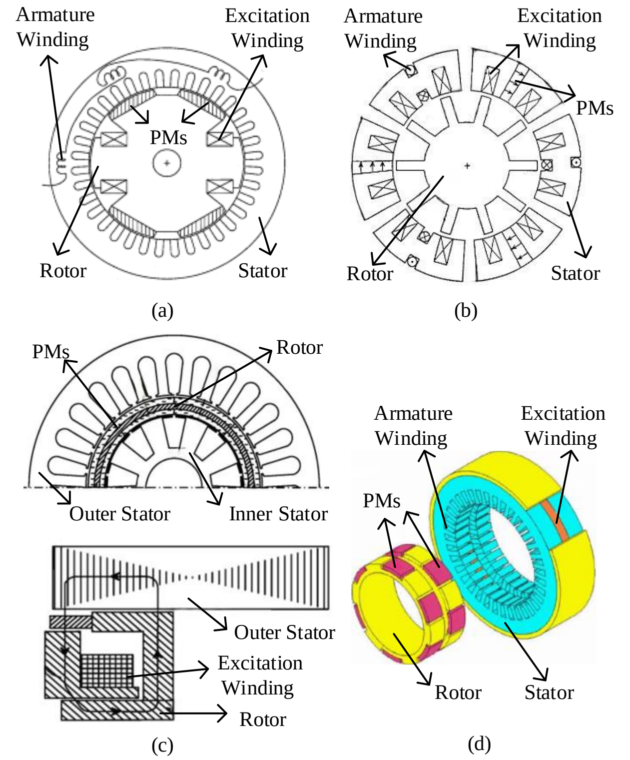

Fig. 9. Hybrid excited PM machines. (a) The PM and excitation coils in the rotor [61]. (b) PM and excitation coils in the stator [62]. (c) Dual-stator HESM [63]. (d) PMs in the rotor and excitation coils in the stator [65].

B. *Hybrid Excited Vernier Type*

Traditional vernier type machines typically face issues such as poor magnetic flux regulation and low power factor. Hybrid excited PMVM (HPMVM) not only expands the constant power operating range but also enhances torque density [68]. The excitation current enhances magnetic flux control capability, making HPMVMs a strong choice for wind power and attracting recent attention.

In [69], Wang et al. presented a multi-phase double-winding HPMVM as the wind power generator, as shown in Fig. 10(a). The stator slots are designed with two sets of windings: one set comprises a three-phase alternating current (AC) winding, while the other consists of a six-phase direct current (DC) winding. These two windings can operate independently, allowing the proposed machine to simultaneously generate both AC and DC power, which is suitable to be arranged for hybrid AC/DC microgrid.

In [70], Wei et al. introduced a dual-stator HPMVM (DS-HPMVM), as shown in Fig. 10(b). It was found that the PMs in the rotor are arranged with consequent-pole Halbach-array, which can achieve a higher power density. Compared with conventional wound field flux-modulated machine, the output torque can be improved by 43% with Halbach-array PMs.

In [71], Liu et al. proposed a flux-controllable HPMVM through DC field winding which is suitable for wind power generation, as shown in Fig. 10(c). Wang et al. compared the HPMVM with different rotor pole designs in [72], both machines use tangentially magnetized slot-opening PMs

(TMSPM) to alleviate the saturation of the stator core. But only the machine with radially magnetized PMs (RMPM) to provide additional magnetic flux.

Yu et al. [73] and Jia et al. [74] studied the HPMVM with DC-biased sinusoidal current in armature windings, as shown in Fig. 10(d). The DC-biased sinusoidal current contains an AC component and a DC component without the need for additional excitation windings. This machine simplifies its structure while simultaneously enhancing torque density, efficiency, and power factor.

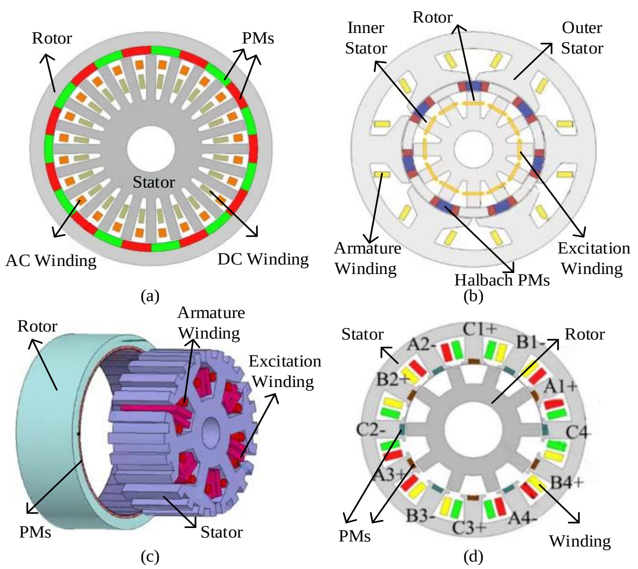

Fig. 10. Hybrid excited vernier PM machines. (a) Multi-phase double-winding HPMVM [69]. (b) Dual-stator HPMVM [70]. (c) HPMVM with salient flux modulation poles [71]. (d) HPMVM with DC-biased sinusoidal current [73].

C. Hybrid Excited Flux-switching Type

Conventional FSPMMs feature simple structures and high reliability but limited flux regulation, reducing efficiency and causing torque fluctuations [75]. The introduction of a hybrid excitation scheme effectively addresses these issues, ensuring the efficient and stable operation of FSPMMs. HFSPM machines have also garnered extensive research attention.

In [76], Hoang et al. presented a 12/10 stator/rotor pole HFSPM, as shown in Fig. 11(a), which is suitable for low-speed gearless wind generator. In [78], Owen et al. introduced a HFSPM with iron flux bridges, as shown in Fig. 11(b). It was found that the iron flux bridges increase coil excitation effectively, and the effect is verified by two-dimensional finite-element analysis and prototype experiment. Wang et al. in [79] presented the control strategy for the structure in [78] to be applied in the field of power generation.

Ullah et al. proposed a HFSPM with H-type modular stator and consequent pole PM rotor in [80], as shown in Fig. 11(c). It was found that modularizing the H-type stator can enhance the electromagnetic performance and torque performance of the machine, the efficiency is elevated to 98.6%. Furthermore, the overall system is easy to manufacture, install, and maintain, making it suitable for large-scale wind power generation.

In [81], Nedjar et al. presented a parallel double excitation HFSPM machine, which found that the excitation coils located within the stator allow for effective control of the air-gap magnetic flux while mitigating the risk of PM demagnetization. This configuration can be utilized in generator applications for wind power generation. Cai et al. also proposed a 12/11 stator/rotor poles parallel HFSPM in [82], as shown in Fig. 11(d). It was found that the excitation coils and armature coils are arranged in an alternating pattern on the Π-shaped segment teeth, with each segment housing one excitation coil and one armature coil. All windings, encompassing the PM, excitation, and armature windings, are positioned on the stationary portion of the machine, which promotes effective thermal management. The magnetic flux paths for the PM and field excitation are independently configured in parallel, thereby improving the magnetic flux regulation capabilities.

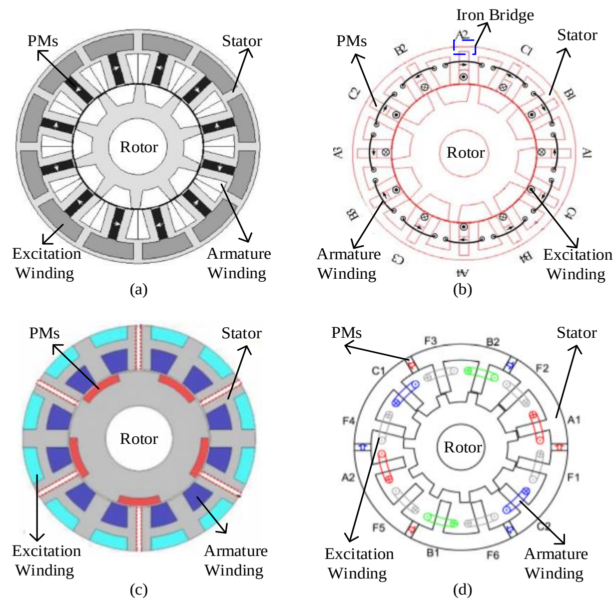

Fig. 11. Hybrid excited flux-switching PM machines. (a) 12/10 HFSPM machine [77]. (b) HFSPM machine with iron flux bridge [79]. (c) HFSPM machine with H-type modular stator and consequent pole PM rotor [80]. (d) Parallel HFSPM machine [82].

D. Hybrid Excited Flux-reversal Type

The FRPM machines are valued for high efficiency and torque [83]. Given that the PMs serve as the sole excitation source in conventional FRPM machines, the magnetic flux regulation capability of the system is constrained, affecting efficiency and performance. Consequently, the development of applications that demand high magnetic flux regulation capabilities, such as wind power generation, may be hindered. Therefore, integrating the concept of hybrid excitation into the FRPM machine presents a promising alternative.

In [84], Wei et al. proposed two asymmetric consequent-pole hybrid excited flux reversal PM (AS-CP-HFRPM) machine topologies, as shown in Fig. 12(a) and (b), it can be found that both structures are developed based on the salient pole rotor. The article derives the relationship between the number of rotor magnetic poles that maximize the average torque and the stator magnetic pole arc (PM ratio) and validates this relationship through global optimization.

In [85], Hao et al. introduced a HFRPM machine with separated excitation stator, as shown in Fig. 12(c). The arrangement of PMs and excitation windings alternately positioned within an internal stator, which is separate from the external stator equipped with armature windings, enhances spatial utilization. Finite element analysis indicates that the 12/11 and 12/13 stator/ rotor poles configurations exhibit improved output performance. Yao et al. presented a partitioned stator HFRPM machine with dual-PM in [86] based on the principle of [85], as shown in Fig. 12(d). The excitation windings are placed in the internal stator, while the PMs are utilized in both the rotor and the external stator. This configuration can exhibit higher torque capacity and flux weakening capability, thereby extending the machine's speed range, which is essential for wind power generation.

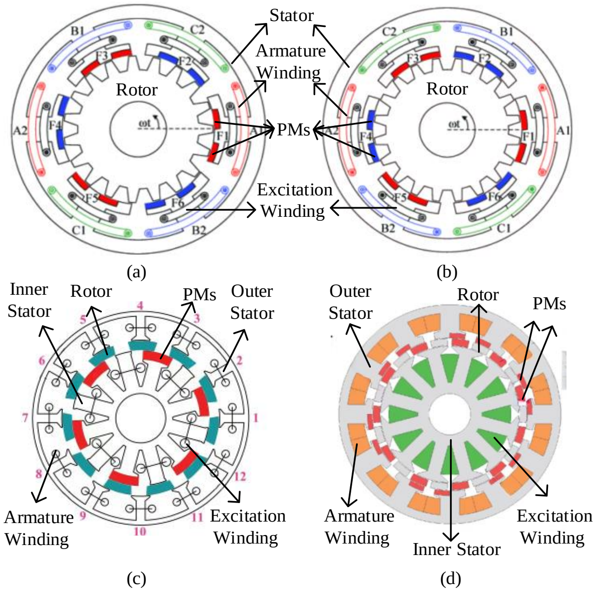

Fig. 12. Hybrid excited flux-reversal PM machines. (a) AS-CP-HFRPM machine with alternately arranged PMs and iron poles [84]. (b) AS-CP-HFRPM machine with PM-to-PM arrangement [84]. (c) HFRPM machine with separated excitation stator [85]. (d) HFRPM machine with dual-PM [86].

TABLE I

COMPARISON OF THE EMERGING DEP-SMP MACHINES

Item	HPMVM	HFSPM	HFRPM
Topology	● Two EPs connect to the armature winding and the excitation winding, respectively ● MP connects to the rotor.		
Efficiency	More than 90%	80%-90%	90%-95%
Power	High	Higher	Much higher
Torque Density	Higher	High	Much higher
Merits	● High speed adjustment ability ● Fast dynamic response	● Low cost ● Flexible design	● High efficiency ● High performance
Weakness	● Poor adaptability at low speed ● Complex control	● Complex manufacturing process	● Complex structure ● High cost ● Complex control requirements

In [87], Wei et al. compared the performance between stator-PM and dual-PM HFRPM machine, which is found that the stator-PM configuration demonstrates good magnetic flux regulation and torque capability during the flux enhancement process. In contrast, the dual-PM configuration exhibits excellent torque capacity in the absence of DC excitation but suffers from poorer magnetic flux regulation capability.

The features of the emerging DEP- SMP machine are briefly shown in Table I.

V. DEP-DMP PMWPGs

The DEP-DMP PM machine is equipped with two EPs, typically using a doubly fed operation. These are connected to the power and control windings, enabling the I/O of electrical energy and control signal. It also has two MPs, which connect two rotors, one of which may be adjustable rings based on magnet flux modulation. This configuration boosts operational efficiency and enhances reliability, ensuring continuous operation if one port fails.

In recent years, brushless doubly fed machines have gained attention in wind power generation. Research on brushless doubly fed machines has yielded a series of significant advancements [88][89]. Integrating the doubly fed concept with magnetic gearing can significantly enhance the performance of traditional MGPM machines by optimizing generator speed based on wind speed fluctuations, thereby improving efficiency. Additionally, the use of flexible control strategies and power electronics helps reduce energy losses and stabilize torque output, making this approach especially valuable for wind power generation.

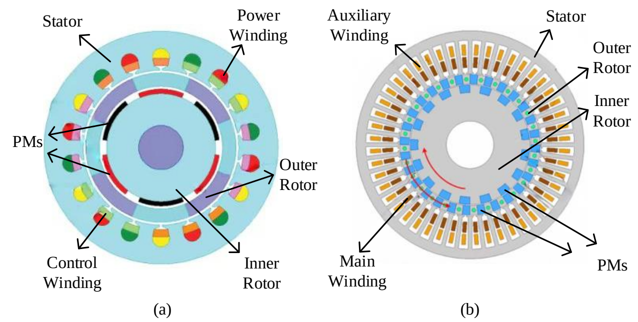

Fig. 13. DEP-DMP magnetic-geared PM machines. (a) Doubly fed MGPM machine with segmented structure [90]. (b) Doubly fed dual-rotor MGPM machine [91].

In [90], Jiang et al. presented the generator with segmented structure based on coaxial magnetic gear, as shown in Fig. 13(a). The segmented design of the rotor and stator effectively reduces high cogging torque and asymmetric EMF caused by control windings, while also improving efficiency and power factor. Luo and Niu introduced a doubly fed MGPM machine for wind power generation in [91], as shown in Fig. 13(b). The outer rotor acts as the primary rotor linked to the blades, while the inner rotor is paired with auxiliary blades to enhance wind energy capture, with both rotors rotating in opposite directions. This configuration effectively doubles the induction frequency due to the relative angular velocity of the main winding. Torque output can be controlled via the main and auxiliary windings.

Jiang et al. proposed a doubly fed double stator double rotor MGPM for wind power applications in [92]. The power winding and control winding are respectively located within the outer stator and inner stator, featuring different pole pair numbers, with the power winding directly connected to the grid. This generator demonstrates high power density, direct-drive capability at low speeds, and excellent grid fault ride-through performance. In [93], Zhang et al. designed a doubly fed generator with interior PM Rotor for wind power applications which has similar external structure to [90]. Both power winding and control winding are located in the stator. It was found that the segmented double rotors could reduce the torque ripple and improve the utilization of PMs and the torque density.

VI. Challenges and Future Trends

The future development of PM machines for wind power generation presents vast prospects; however, it also faces numerous challenges. The primary challenges and future trends associated with PMWPGs are summarized as follows:

A. Structure and Materials

PM machine performance relies on high-quality rare-earth PMs, which are costly. Developing alternative materials and integrating PMs with new designs is essential for advancing the generators towards small-scale and enhanced performance, which is a prevailing trend in current.

B. Power Density

Further enhancement of generator power density remains a primary trend. By implementing concepts such as doubly fed or hybrid excitation systems, the optimization of structures can be achieved, leading to increased power output while reducing losses during operation, enhancing the torque performance.

C. Reliability and Durability

Generators operating in wind power applications are subjected to harsh operating conditions, including high temperatures, high humidity, and vibrations. Consequently, improving the reliability and durability of these generators is a significant research direction.

D. Intelligentization and Digitalization

Presently, intelligentization and digitalization are challenges faced across various industrial sectors, driven by the demands of the modern era. Applying intelligent technologies for real-time monitoring, fault diagnosis, and adaptive control is essential for improving PMWPG performance and reliability.

VII. Conclusion

This paper has presented a comprehensive review of PM generators for wind power generation in terms of challenges and opportunities. According to the number of EP and MP contained in the machine, the PMWPG is classified into SEP-SMP, SEP-DMP, DEP-SMP, DER-DMP.

SEP-SMP machine has the relatively simplest structure, the EP is connected to the armature winding for the I/O of electrical energy. The MP is connected to the rotor for the I/O of mechanical energy. In addition, PMVM, FSPM and FRPM types developed in the later period are separately explained and compared with the conventional gear-boxed type. SEP-DMP machines usually have two rotors, and the article discusses two types, MGPM and TFPM. In addition, the DEP-SMP structure mentioned in this paper focuses on hybrid excitation. The two EPs are connected to the armature winding and the excitation winding respectively, and the excitation winding introduces the excitation current to control the magnetic flux and improve the performance. This paper discusses and analyzes the traditional hybrid excited type and the emerging hybrid excited structure based on SEP-SMP structures. DEP-DMP machine introduces the concept of doubly fed double rotors into the machine and focuses on the analysis of the MGPM.

Wind power is currently centered on PM generators, which face several challenges. This paper outlines these challenges and future trends for PMWPGs. In addition, all mentioned topologies have been lab-validated but will face unique challenges in practical applications.

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