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Issues Related to the Structural Design of Wind Power Generators

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Abstract- Wind power generation is a highly important part of the development of renewable energy systems. In particular, offshore wind power is being actively developed in Taiwan. Offshore wind power systems and grid-connected technologies are worthy of attention. In addition to power system analysis, the structural design and principles of wind power generators (WPGs) as well as the possible methods for improving their performance should also be studied. A variety of generators can be used in wind turbines, such as permanent magnet synchronous, permanent magnet reluctance, switched reluctance, and superconducting generators. However, different generators have different characteristics and uses. This study explores the advantages and disadvantages of various types of WPGs. We review the current structural design principles of WPGs, including power generation efficiency, cogging torque, torque ripple, output power, materials, cost and reliability. These factors can be used as important criteria for the future design of WPGs in terms of the stator/rotor structure and performance.

Keywords- *Wind Power Generator (WPG), Structural Design, Permanent Magnet Synchronous Generator (PMSG), Permanent Magnet Reluctance Generator (PMRG), Switched Reluctance Generator (SRG), Superconductor Generator (SG), Cogging Torque*

I. INTRODUCTION

Wind turbines convert wind energy into electricity for distribution in the grid. Traditional horizontal-axis turbines consist of three major components (as shown in Fig. 1): (a) The rotor, which includes the blade and converts wind energy to low-speed rotational energy, and its cost is approximately 20% of that of a wind turbine. (b) The generator assembly, which converts low-speed input rotation to high-speed output rotation for power generation, and its cost is approximately 34% of that of a wind turbine; it includes the components of the generator (Goudarzi, 2013; Goudarzi & Zhu, 2012), control electronics, commonly used gearbox (e.g. planetary gearbox), adjustable-speed drive, or continuously variable transmission. (c) The surrounding structure, which includes the yaw mechanism of the tower and the rotor, and its cost is approximately 15% of that of a wind turbine.

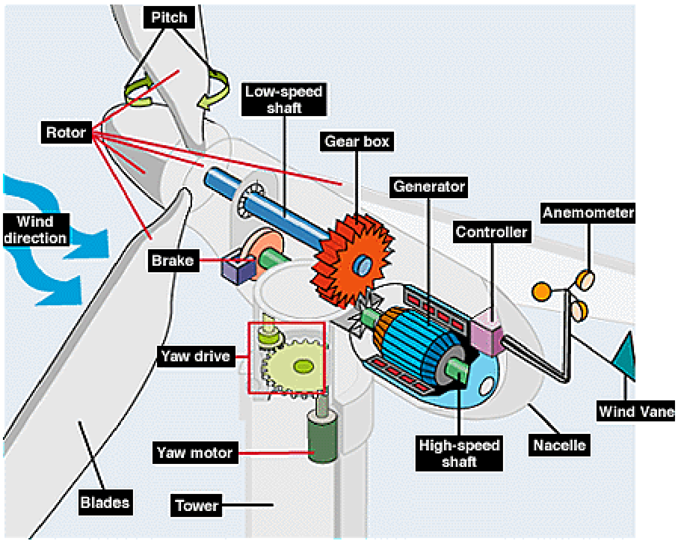

Figure 1. Components of a conventional horizontal-axis wind turbine (Saad & Asmuin, 2014)

With the growth of power demand and environmental awareness, the development of renewable energy has attracted increasing attention, and various renewable energy technologies have been developed. Among them, wind power is an ideal choice for power generation. Moreover, with the rapid development of wind power technology, several types of generators (Kim & Lu, 2010; Polinder, 2011) have been successively applied to wind power generation systems. They include Induction Generators (IGs), Permanent Magnet Synchronous Generators (PMSGs), Switched-Reluctance Generators (SRGs) and Flux-Switching Permanent Magnet (FSPM) machines. Among them, IGs are a common type of early wind power generators owing to their simple structure and low price (Bansal, 2005; Grauers, 1996). However, IGs require virtual work compensation components, and most of them require gearbox design, resulting in low efficiency and reliability. Accordingly, direct-drive PMSGs have attracted attention owing to their simple structure, high energy field, high efficiency and low maintenance cost. However, the main problem of this type of generator is the high cost of the Permanent Magnet (PM). To reduce the cost of wind turbines, some wind turbine manufacturers have developed reluctance WPGs (Boldea et al., 2014) and FSPM WPGs (Boldea et al., 2014; Lin & Zhu, 2008; Yan et al., 2009). The design principle of reluctance WPGs is to use the WPG structural design to make the magnetic flux pass the path of lower reluctance, thereby reducing the iron loss and improving efficiency. In fact, an FSPM machine is a combination of a brushless PMSG and a switched-reluctance machine (Thongprasri & Kittiratsatcha, 2014; Chouitek et al., 2014; Chen & Zhu, 2010); therefore, it has the advantages of higher power and torque density, smaller volume and weight, higher reliability, rigid structure and fault tolerance compared with both PMSGs and Doubly Fed Induction Generators (DFIGs) (Thongprasri & Kittiratsatcha, 2014; Chouitek et al., 2014; Chen & Zhu, 2010; Fei et al., 2012; Chen & Nilssen, 2010; Wei et al., 2006), thus suggesting the feasibility of FSPMs for direct-drive wind turbines as successors of PMSGs (Zohoori et al., 2014; Ojeda et al., 2012; Christopher et al., 2014).

For the past few years, megawatt wind turbines have been increasingly applied in maritime applications. As the size of wind turbines increases, their weight and volume also increase. For example, a 10 MW conventional direct-drive PM generator weighs approximately 300 tons (Terao et al., 2013). Therefore, to reduce the weight of wind turbines, superconducting materials have begun to be applied to the structural design of WPGs. Owing to their small weight, small size and high efficiency, superconducting materials have become one of the choices of WPG materials. Using superconducting instead of copper coils can effectively reduce the volume and weight of WPGs. Currently, research on superconducting materials in wind turbines includes the position of superconductors in WPGs (such as partial superconduction or full superconduction) and the topological structure of superconducting generators. In addition, some studies have also analysed the characteristics of superconducting WPGs and PMWPGs (Terao et al., 2013; Kudrjavtsev et al., 2015; Tariq et al., 2011; Eriksson & Bernhoff, 2012).

Recently, the megawatt wind generators, particularity applied in offshore area, e.g., Taiwan Strait, become more popular. That is, the size of the wind turbine generators becomes large. For instance, the weight of a 10 MW conventional Direct-Drive Permanent Magnet Synchronous Generator (DDPMSG) is around 300 tons (Lin & Zhu, 2008; Y. Terao et al., 2013). The cost of a typical offshore wind turbine is two to three times the cost of onshore wind turbine, while costs of turbines and their assembly account for 22.1% and 11.1% of the total cost (Moné et al., 2017). This article discusses how the structural design types of WPGs affect the performance of wind turbines, and provides the suggestions for future R&D, which will definitely contribute to the on-going offshore wind power construction in Taiwan Strait.

II. Magnet Materials of Wind Power Generators

The magnet materials applied in WPGs can be roughly classified into Ferrite, AlNiCo and rare-earth materials. Ferrite is one of the oldest materials used in the field and is corrosion resistant and inexpensive (Kudrjavtsev et al., 2015). However, its disadvantage is that a large amount of material is required in the manufacturing process, resulting in large (Kudrjavtsev et al., 2015) and overweight wind turbines.

In addition to satisfactory corrosion resistance, AlNiCo materials are more tolerant in high-temperature environments (Kudrjavtsev et al., 2015). Their working temperature can be as high as 600°C, with the advantages of easy processing and non-deformation. However, the nonlinear hysteresis curve of AlNiCo causes difficulty in temperature design (Kudrjavtsev et al., 2015). Magnets made of rare-earth materials have high energy density, which can effectively reduce the amount of magnetic material, thereby reducing the manufacturing cost. However, their disadvantages are poor heat resistance, low corrosion resistance and high cost (Tariq et al., 2011). By combining the characteristics of WPGs using these magnetic materials, new types of WPGs have being developed, including SRG, PM SRGs and FSPM WPGs, in which the amount of magnetic material is reduced, or even the need for using magnets is eliminated.

III. STRUCTURE OF WIND POWER GENERATORS

A generator is a device that converts kinetic or other forms of energy into electricity. First, a prime mover converts energy from various primary sources into mechanical energy, which is then converted into electric energy through the generator. Subsequently, the electricity is sent to consumers through a distribution network. In general, a generator uses hydraulic or wind power to rotate the coil between the poles of a magnet; when the coil rotates, the magnetic field in the coil changes, thus generating an induced current. This is a method for generating electrical energy by a power conversion mechanism based on the principle of 'electromagnetic induction'.

Generators can be classified into two types: (1) Axial magnetic field generators, (also called disk generators) in which the direction of the main magnetic field is axial; the axial direction is small and the radial size is large. (2) Radial magnetic field generators, in which the direction of the main magnetic field is radial, and the axial dimension is large. They are also called cylindrical generators and are widely used.

A. *Permanent Magnet Wind Power Turbines*

Owing to their simple construction, PMWPGs have become increasingly widespread (Eriksson & Bernhoff, 2012; Barcaro & Bianclu, 2012; EL-Refaie, 2010). They have a magnet arrangement on the rotor side and a winding mounted on the stator side. PMWPGs do not use brushes and slip rings, and their power generation is efficient and reliable. However, owing to the high price of the magnets, PMWPGs are expensive to manufacture. In addition, there is a demagnetisation effect. In general, PMWPGs can be classified according to the rotor position based on the magnetisation direction.

According to the magnetisation direction, PMs can be classified into three categories (Jian et al., 2009; Husain et al., 2016; Brad et al., 2017): Radial-flux, axial-flux and transverse-flux. Structurally, radial magnetisation indicates that the magnetisation direction is perpendicular to the mechanical bearing. In axial magnetisation, the magnetisation direction is parallel to the mechanical bearing. Radial magnetising WPGs are widely used. Therefore, the literature on the structural design of radial magnetising PM generators is also most extensive. The relevant studies are as follows:

Chen et al. studied the design of externally transformed PMWPGs (Chen et al., 2005). Their structure was simulated by finite element analysis, and their effectiveness was verified. In WPGs, cogging torque may cause noise and vibration. In a PM generator, cogging torque is caused by the interaction between the rotor and the stator slot. This is also known as detent or 'no-current' torque. Cogging torque is position-dependent, and its periodicity per revolution depends on the number of magnetic poles and the number of teeth on the stator. Cogging torque is an undesirable feature for the operation of PM generators. Jerkiness is particularly prominent at lower speeds. Cogging torque causes torque ripple as well as speed ripple; however, the inertia moment of the generator filters out the effect of cogging torque at high speeds. Therefore, in the design of a WPG, reducing the cogging torque is an important issue. Several methods have been developed for reducing the cogging torque, including the chute structure (Kudrjavtsev et al., 2017), inclined magnet, and slot ratio designs.

To reduce the cost of magnets in WPGs, AlNiCo magnets are used instead of general ferrite magnets, and magnetic-flux-concentrated rotors are installed to resolve the demagnetisation problem of AlNiCo materials (Faiz et al., 2016). Arafat et al. (2016a) proposed fractional-slot internal rotors to reduce the cogging torque of PMWPGs.

To improve the performance of WPGs, an optimised design method has been proposed to reduce the amount of magnetic material and conductor copper (Almandoz et al., 2016). In addition, Chirca et al. (2016) proposed a multi-phase design and a rectifier circuit that can also reduce the cogging torque. Moreover, Melcescu et al. (2017) used a dual-rotor structure to increase the conversion efficiency of WPGs. In Chirca et al. (2016), a radial rotor structure was also used because the magnetic flux becomes more concentrated in the rotor, and thus more space is reserved for the magnet.

Buried radiant rotors and slotted structures have been designed to achieve high torque and low voltage regulation (Li et al., 2015). Furthermore, different types of groove and fractional-slot designs have been proposed to reduce the cogging torque, thus increasing the power generation efficiency (Arafat et al., 2016b).

Axially magnetised PM generator is another type of WPGs. For example, Brad et al. designed an axially charged WPG in which finite element analysis was used to calculate the air gap flux density (Latoufis et al., 2016). Owing to the poor corrosion resistance of rare-earth magnets, ferrite or other non-rare earth magnets are used as magnetic material for axially magnetised PM generators. In addition, Jamali Arand & Ardebili (2016) used slanting magnets to reduce the cogging torque of a direct-drive wind turbine.

There are few studies on lateral magnetising WPGs. Only Husain et al. discussed the design of WPGs for direct-drive lateral magnetisation, where flux-concentrating magnets were used. This increases the pole pitch, thus improving the WPG performance, torque density and power factor (Husain et al., 2016).

B. *Wind Power Generators Based on Flux Switching*

In 1950, the first flux-switching WPG was proposed (Rauch & Johnson, 1955). It has the advantages of simple structure and high torque density. Its magnets and windings are mounted on the stator side, making this WPG easier to use in high-speed work environments. In addition, the amount of copper on the stator side is also greatly reduced. However, the traditional magnetic-flux-switching WPG uses a relatively large number of magnets, thus increasing manufacturing cost. To resolve this, new types of flux-switching WPGs have been proposed (Zhu & Chen, 2010; Chen et al., 2008; Thomas et al., 2009). They can be mainly classified into three structural types: C-core, E-core and multi-tooth, as shown in Figs. 2 (b), (c) and (d), respectively. The main design principle of these WPGs is to reduce the number of magnets. As shown in Fig. 2 (b), this number is reduced to two magnets in Fig.2 (b) from four magnets in Fig. 2 (a).

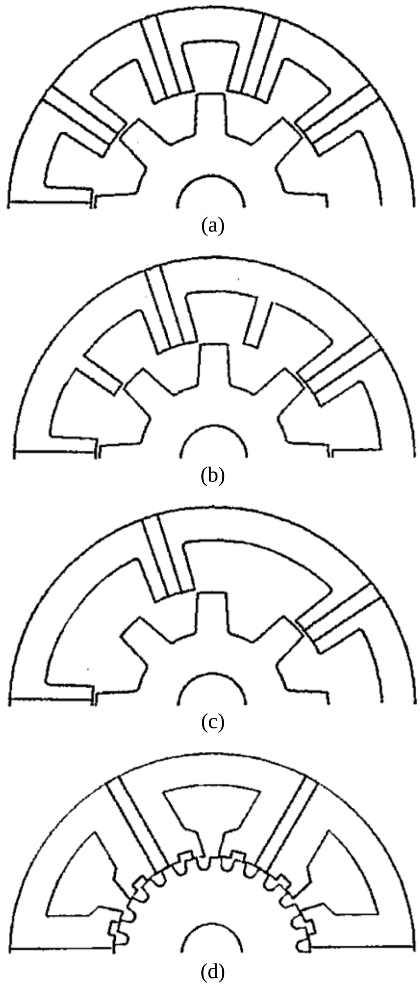

Figure 2. a) Traditional structure, b) E-core structure, c) C-core structure, d) Multi-tooth structure

C. *Reluctance Magnet Wind Power Generators*

These WPGs include switched-reluctance and PM reluctance generators. The structural design of traditional PMWPGs requires high-priced magnet materials, and some methods have been proposed to resolve this (Boldea et al., 2014). For example, new WPGs use ferrite magnets or no magnets at all. Switched-reluctance WPGs do not use magnet design patterns (Cheng et al., 2009; Richter & Ferreira, 1995; Cardenas-Dobson et al., 1995; Radun et al., 1998). Mueller proposed a switched reluctance WPG with a power of 20 kW and a rotational speed of 100 rpm (Mueller, 2005). The rotor structure of a switched-reluctance WPG is of salient pole type, the material is completely composed of silicon steel sheets and the windings are mounted on the stator side. As the rotor does not use magnets and winding, its structure is simple; further, as no magnet is required, permanent magnet demagnetisation is not an issue. Switched-reluctance WPGs generally require no gearbox; thus, low cost, high reliability and high performance can be achieved. However, the control system of a switched reluctance WPG is not easy to design, and this is a disadvantage of this type of WPG.

PM reluctance WPGs are an improvement of switched-reluctance WPGs, as a magnet is added between the teeth on the stator side. Other than that, the structure of PM reluctance WPGs is the same as that of switched-reluctance WPGs. For example, the rotor side also adopts a salient pole structure, and the windings are only mounted on the stator side. Owing to the addition of the magnet, PM reluctance WPGs do not require exciting circuits and position sensors. In addition, the added magnet is on the stator side, and thus the efficiency and output power of PM reluctance WPGs are higher than those of switched-reluctance WPG. Nakamura & Ichinokura (2012) discussed the structural design of PM reluctance WPGs. They pointed out that if the shape of the magnet is changed, the torque ripple can be reduced.

D. *Wind Power Generators Based on Superconducting Materials*

For large wind turbines, superconductor WPGs represents the latest trend. Compared with other types, these WPGs have high efficiency, small weight, small size and low noise (Kalsi et al., 2004). As the coil is made of a superconductor, it is lightweight and has an air gap flux density of 1.5 to 2.0 T, which is twice as much as that of a conventional WPG. Superconductor materials were discovered as early as 1911, but at that time, they were at an experimental stage, and their properties were poorly understood. Stekly et al. (1966) designed the first superconductor WPGs. In this type of wind power generator, the superconductor coil is mounted on the rotor and stator side. In recent years, superconductor materials have been greatly developed. According to their critical temperature, superconductors can be divided into two major categories: high- and low-temperature (Wang et al., 2015; Wen et al., 2015). Niobium-Tin is a low-temperature superconducting material discovered in 1955. Around 1980, high-temperature superconducting materials (such as copper oxy-calcium-titanium ceramic materials) were discovered; they have the advantages of high-temperature resistance and low price.

Karmaker et al. (2015) explored various structures of superconductor WPGs, including core type and rotor salient pole as well as rotor non-salient pole structures. It has been demonstrated through experiments that the salient pole structure has satisfactory performance, and its price is relatively low. Moreover, a 12 MW radial magnetising direct-drive superconductor WPG was designed and tested for distinguishing the differences between high-temperature and low-temperature conductor materials on the rotor side (Wang et al., 2015).

Although high-temperature superconducting WPGs have several advantages, they are costly, heavy and bulky. In addition, as high-temperature superconductor materials are expensive, there are still no mature products on the market. Currently, low-temperature superconductor materials are still the mainstream.

E. *Summary*

In summary, there are several issues to be considered in WPG design, including low cost, high efficiency and high reliability. High cost WPGs are difficult to survive on the market. Table 1 presents a comparison of the characteristics of various WPG configurations. It can be seen that most superconducting WPGs have a competitive advantage, but their cost is excessively high. SRGs have the advantages of low cost, simple structure and high efficiency, but their main disadvantage is their large size. Currently, the mainstream of WPGs is PMSGs, but they are complicated and costly. Therefore, there is still room for improvement.

TABLE I. PERFORMANCE COMPARISON OF VARIOIUS TYPES OF WPGs

	PMSG	SRG	PMRG	SCWPG	FSPMG
Cost*	High	Low	Medium	Very High	Medium
Structure	Complex	Simple	Medium	Medium	Complex
Size	Large	Extremely Large	Little Small	Small	Large
Efficiency (%)	High (92- 97)**	High (95)***	High (98)****	Extremely High (~100)*****	High (94)******

*: Costs are basically compared by prices of construal materials, excluding the costs of maintenance and the factor of running life.(Moné et al., 2017; Nyanteh et al,. 2015)
**: https://www.mdpi.com/1996-1073/13/4/1004/pdf
***: https://kknews.cc/zh-tw/car/2bm58n9.html
****: https://ir.nctu.edu.tw/bitstream/11536/44747/1/459001.pdf
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******: http://ir.lib.ntust.edu.tw/bitstream/987654321/14819/1/NSC98-2221-E011-148.pdf

IV. METHODS FOR IMPROVING THE PERFORMANCE OF WIND POWER GENERATORS

Different types of WPGs have been designed with different considerations, such as maintenance cost, power conversion and matching with mechanical systems. The electrical performance of WPGs can be assessed in terms of output power, power generation efficiency, cogging torque, torque ripple, reliability, cost and corrosion. Therefore, in the design of a WPG, these aspects should be considered. In this section, we will explore the improvement of various characteristics of

WPGs by changing their structure and materials. Corrosion and wind strength are special design factors for offshore wind turbines.

A. Efficiency

Efficiency is a major consideration in the structural design of WPGs. In Oh et al. (2014), a new type of laterally magnetised PM reluctance WPG was proposed. It is matched with a stator-side U-shaped iron core to reduce the magnetic flux path. However, high manufacturing cost is a major drawback of these WPGs. In that study, the structure of the improved rotor was also used to increase the efficiency of wind turbine power generation. Power generation efficiency can be improved by changing the pole number and pitch factor of the rotor (Shao et al., 2017). Regarding the structure of the outer rotor of PMWPGs, the E-limit difference method was used in Rastogi et al. (2016) to improve power generation efficiency, and the finite element method was employed to verify the improvement; according to the simulation results, the weight and loss of the WPG were significantly improved after the optimised method was applied. Fractional-slot concentrated winding PMWPGs can be tested using different types of magnets and different combinations of slot numbers (Sergeant & Bossche, 2014). The results demonstrate that WPGs using ferrite magnets are less efficient than WPGs using rare-earth magnets. Husain et al. improved the efficiency of laterally magnetised PMWPGs by testing different combinations of slot numbers. Most superconductor WPGs are of direct-drive type, and owing to the combination of power converters, efficiency is reduced and the cost of the entire system increases. To resolve these problems, Liu et al. proposed generators with superconductor coils, in which central and distributive windings are used to determine the final winding so that power generation efficiency may be improved (Liu, et al., 2017).

From the above discussion, the methods for improving the efficiency of a WPG from the perspective of structural design include changing the number of poles and the pitch of the rotor, fractional-slots with concentrated windings, changing the number of slots and changing the magnetic materials.

B. Cogging Torque

Cogging torque occurs in a WPG with a PM structure, such as a PM generator. The reason for this is the interaction between the rotor side magnet and the stator side groove (Bianchi & Bolognani, 2002). Excessive cogging torque can cause mechanical shock and noise. Therefore, it is necessary to minimise the cogging torque at the design stage.

Cogging torque can be reduced by increasing the number of phases. Ichinokura et al. (2006) pointed out that three-phase PM reluctance WPGs have lower cogging torque than single-phase PM reluctance WPGs. In Huang et al. (2017), a two-stator superconductor WPG with centralised winding was proposed, and the cogging torque of the rotor was reduced by changing the shape of the rotor magnet. The combination of the number of slots and poles is another factor that may affect the cogging torque of the turn. Chirca et al. (2016) proposed that the poles of 20 rotors and 21 stators in a PMWPG can reduce the cogging torque and achieve the desired torque. The centrifugal force of the rotor will also affect the cogging torque. If the centrifugal force of the cogging rotor is overly large, the torque will be relatively increased. Hsieh & Yeh (2013) studied the effect of the centrifugal force of the PMWPG's rotor. The structural design of the inclined groove can also reduce the cogging torque of a WPG. This was discussed in Kudrjavtsev et al. (2017). Arafat et al. (2016a) discussed the design of a PMWPG's internal rotor. The study pointed out that to achieve smooth rotation in low-speed WPGs, the cogging torque should be reduced at the design stage. Therefore, in that study, the cogging torque was reduced by using a fractional groove. In addition, Arafat et al. reduced the cogging torque by changing the groove shape and using a fractional groove. This also improved efficiency (Arafat et al., 2016b).

According to the above discussion, reducing the cogging torque of a WPG is an important consideration in the design of wind turbines. The related methods include changing the shape of the rotor magnet, the number of slots, the centrifugal force of the rotor, the structure of the inclined groove and using fractional slots.

C. Reliability

Improving the reliability of WPGs is also an important element in the design of wind turbines. Higher reliability implies longer life and lower maintenance cost. Most superconductor WPGs are equipped with a cooling system, and their coils are connected in series. However, if one of the coils fails, it will affect the overall function. Therefore, in Go et al. (2017), it was proposed that each coil be equipped with its own independent cooling system, so that a dysfunction of a coil will not affect other coils. In Yang et al. (2016), a superconductor WPG cooling-free system was proposed. This design can improve the reliability of the WPG, but its structure is considerably more complicated than that of general superconductor WPGs. In addition, Melcescu et al. (2017) proposed a WPG with dual-rotor design that consists of a PMWPG and an induction machine. This type of wind turbine can increase the conversion efficiency between energy and power, and system reliability is improved because it is not necessary to use a slip ring and a brush.

D. Cost

Low-cost wind turbines are more competitive. Nyanteh et al. (2015) proposed a new type of 4X conductor material, namely, beryllium copper oxide (YBCO), which is used to increase the current density and reduce the cost of high-temperature superconductor materials, thereby reducing manufacturing cost. These materials can improve the performance of the original conductor. The current density of the new conductor is four times as high as that of the original conductor, hence the term '4X conductor'.

To reduce the cost of the magnetic material, an effective method is to use AlNiCo magnets instead of rare-earth magnets. Faiz et al. (2016) proposed a structural design of a magnetic-flux-concentrated rotor that not only resolves the problem of demagnetisation of AlNiCo magnets but also reduces manufacturing cost. Structural optimisation is indispensable for achieving better WPG performance. Almandoz et al. (2016) pointed out that the amount of magnetic material can be reduced using optimisation tools. Latoufis et al. (2016) also indicated that the production cost of axial-flux PMWPGs can be effectively reduced if ferrite magnets are used instead of rare-earth magnets. In addition, Husain et al. (2016) also proposed that transverse PMWPGs use ferrite magnets instead of the original rare-earth magnets, thereby reducing manufacturing cost.

In summary, the methods for reducing the cost of WPGs include using lower-cost magnetic materials, improving the current carrying density by coil conductors, improving the rotor structure design and optimising the design by using optimisation software.

E. Output Power

If the output power of a WPG is increased, its performance is improved. It has been demonstrated that the windings can be changed to increase the phase voltage and output power of a WPG, as in, for example, the dual field winding (Park et al., 2015). Dual field winding refers to the original coil being split into two parts, one on the inner stator side and the other on the outer stator side; the inner stator is inside the rotor, and the outer stator is outside the rotor. However, such WPG structures are more complex, and thus additional frictional loss is inevitable.

In conventional flux-switching WPG, certain silicon steel sheets cannot be used efficiently, thus causing magnetic saturation of the teeth. To alleviate this, it has been proposed that the magnet should be placed on the inner stator side instead of the outer stator side. In Chirca et al. (2016), the magnetic flux on the rotor side of a radiating PMWPG was more concentrated, thus providing more space for additional magnets to increase their power density.

F. Torque Ripple

Cogging torque can cause noise and vibration. In Dhifli et al. (2016a) and Dhifli et al. (2016b), the quasi-3D finite element method was used to assess the performance of WPGs. These studies indicate that torque ripple can be reduced and torque can be increased by optimising the tooth width. Saeed et al. (2016) proposed a flux-switched WPG with dual-rotor and multi-tooth structure that is designed to reduce torque ripple. Moreover, a PM reluctance WPG with stacked structure was proposed to reduce the cogging torque (Melcescu et al., 2017). The original steel sheet on the stator side was cut into three equal parts along the bearing and the bearings were strung together. In that study, the shape of the rotor-side magnetic poles was also changed. The results demonstrate that torque ripple can be further reduced.

G. Corrosion

The rare-earth magnets used in PMWPGs are susceptible to corrosion. There are generally two different methods for alleviating this: applying a corrosion-resistant material on the surface of the magnet, and using a ferrite magnet because this type of magnet has satisfactory corrosion resistance. In Eriksson & Bernhoff (2012), the latter was used to resolve the problem of magnet corrosion in PMWPGs.

V. Methods and Tools for Structural Design of WPGs

Effective analytical methods and tools are required in the design of WPG structures. Two methods are commonly used to analyse WPG performance, namely, Magnetic Circuit Analysis (MCA) and Finite Element Analysis (FEA). The former is rough and inaccurate. The construction of the equivalent magnetic circuit is used to obtain a rough design outline, and for beginners, this method is simple and easy to use. However, it is highly important to obtain accurate simulations for WPG design. FEA can obtain relatively accurate calculation results, but its shortcoming is that it is computationally expensive. If the stator and rotor structure of a WPG are symmetrical, 2D FEA may be used; otherwise, 3D FEA is used.

A large number of commercial simulation software packages are available that provide tools for WPG structural analysis, such as SPEED, PSIM, Flux, ANSYS and JMAG. With the development of these tools, users need not write programs to analyse the performance of WPGs, thus greatly facilitating the analysis process.

In addition, we suggest the use of experimental data to verify the accuracy of the analytical results, which can be used as a criterion to select 2D or 3D FEA. The general steps for conducting experiments first focus on the analysis of design factors, such as stress, strain, vibration, internal force and reaction force of the components, by which discover whether there are major operational problems caused by component interferences in the system. If there is no problem with the collocation of all designed components, the prototype composed of which can then perform performance tests, such as operating life, fatigue resistance, power generation efficiency, as well as harsh environment and accelerated life tests. Basically, only designed products or machines that have undergone experimental certification are eligible for commercialization and mass production.

VI. CONCLUSIONS

We discussed the structural design of the main body of WPGs. We focused on important issues to be considered in the design of the WPG structure, including the comparison of magnet materials, the consideration of different stator and rotor structures, and the improvement of the performance of WPGs. Some possible structural designs were identified to improve WPG efficiency, reduce cogging torque, reduce manufacturing costs, increase output power, reduce torque ripple, as well as other performance improvements. Through this discussion, we can understand the key points of WPG structural design, thus improving the overall efficiency of wind turbines.

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