Trends in Wind Turbine Generator Systems

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***Abstract*—This paper reviews the trends in wind turbine generator systems. After discussing some important requirements and basic relations, it describes the currently used systems: the constant speed system with squirrel-cage induction generator, and the three variable speed systems with doubly fed induction generator (DFIG), with gearbox and fully rated converter, and direct drive (DD). Then, possible future generator systems are reviewed. Hydraulic transmissions are significantly lighter than gearboxes and enable continuously variable transmission, but their efficiency is lower. A brushless DFIG is a medium speed generator without brushes and with improved low-voltage ride-through characteristics compared with the DFIG. Magnetic pseudo DDs are smaller and lighter than DD generators, but need a sufficiently low and stable magnet price to be successful. In addition, superconducting generators can be smaller and lighter than normal DD generators, but both cost and reliability need experimental demonstration. In power electronics, there is a trend toward reliable modular multilevel topologies.**

***Index Terms*—Direct-drive generators, doubly fed induction generators (DFIGs), generator systems, permanent magnet (PM) generators, wind energy, wind turbines.**

I. Introduction

The objective of this paper is to review the trends in wind turbine generator systems and to describe a number of possible future generator systems. Although there are also smaller wind turbines, this paper focuses on large wind turbines. Fig. 1 shows how the wind turbine size has grown over the past decades [1]. Also the wind turbine market has grown significantly over the past decades [1].

This paper starts with discussing some important requirements and basic relations for wind turbine generator systems. Next, it describes the four most commonly used generator systems in wind turbines. Subsequently, it reviews some important possible future wind turbine generator systems. It closes with concluding remarks.

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Fig. 1. Development of power and size of wind turbines. Source: Bundesverband WindEnergie e.V.

II. Requirements and Basic Relations

A. Requirements

The key objective of the developments in wind turbines is to minimize the cost of energy delivered to the power system. The contribution of the generator system to this objective is to convert the mechanical input energy from the blades into electrical energy, again enabling minimization of the cost of energy. This has a number of important implications.

1) Capital expenditures (such as manufacturing, transportation, and installation) are important, but not decisive, because operational expenditures (such as repair and maintenance) also have to be considered.
2) What is the best generator system varies over time because the material cost varies over time, as we have seen for permanent magnets (PMs). Uncertainty about these price developments influences decisions.
3) What is the best generator system depends on the location where the turbine is installed, because the total energy produced depends on the wind speed.
4) The efficiency of the system is important, but not decisive, because a system with a lower efficiency that delivers energy at a low cost of energy is better.

Besides fulfilling this key objective, wind turbine generator systems have to meet a number of other requirements.

1) Grid Connection: To enable large-scale application of wind energy without compromising power system stability, power system operators have grid codes to describe the requirements for the quality and the form in which the power is delivered to the system [2]. Wind turbines are required to grid-fault ride-through [or low-voltage ride-through (LVRT)] capability: they have to stay connected and contribute to the grid in case of a disturbance such as a voltage dip. On the long term, wind farms should—similar to conventional power plants—supply active and reactive power for frequency and voltage control in the power system.

2) Reliability and Availability: Especially offshore, operational expenditures may form a significant part (in the order of 30%) of the cost of energy. Therefore, requirements related to reliability, availability, and maintainability are getting more attention and more research in this field is necessary [3]–[9]. Proper protection against the aggressive humid and salty offshore environment is extremely important.

3) Variable Speed: To enable an optimal match between the generator system and the aerodynamic of the rotor, the generator system is required to have a variable speed. The power that can be captured from the wind with a wind turbine is given by [1]

$$P = \frac{1}{2}\rho_{\text{air}} C_p(\lambda, \theta)\pi r_b^2 v_w^3 \tag{1}$$

where ρ_{air} is the air mass density, v_w is the wind speed, r_b is the rotor radius (or the blade length), and C_p is the power coefficient, which depends on the specific design of the blade, the blade pitch angle θ, and the tip speed ratio λ (blade tip speed divided by wind speed). The power coefficient is maximum for a constant tip speed ratio, and therefore at a rotational speed proportional to the wind speed.

B. Generator Scaling

The cost of a generator depends on the size and the materials used. The size of the generator is in first approximation proportional to the rated torque. The shear stress (the force per square meter of active air-gap surface area) in electrical machines is given by [10]–[12]

$$F_d = \frac{1}{2}\hat{A}_s \hat{B}_g \cos\gamma \tag{2}$$

where $\hat{A}_s$ and $\hat{B}_g$ are the amplitudes of the fundamentals of the stator current loading and the air-gap flux density, and γ is the angle between them.

This shear stress is rather constant over a wide range of machine types and power levels, because it is the product of the flux density, which is limited because of saturation, and the current loading, which is limited because of dissipation. By using forced liquid cooling, this shear stress can be increased [10], but at the cost of reducing the efficiency.

With this shear stress, a first estimate of the generator dimensions of a radial flux generator can be made. The power produced by a radial flux generator is given by [12]

$$P = \omega_m T = 2\pi\omega_m r_s^2 l_s F_d = 2\omega_m F_d V_r \tag{3}$$

where ω_m is the mechanical angular speed, r_s is the air-gap radius, l_s is the axial stack length, and V_r is the rotor volume of the generator.

The torque level of the generator system increases more than proportional to the power level. This is because the blade tip speed must be limited to avoid excessive mechanical forces, wear, and audible noise. If the rated blade tip speed v_{trated} is assumed independent of the size of the rotor, then the mechanical rotational speed of the rotor ω_r is inversely proportional to radius of the rotor. The rated torque can then be written as

$$T_{\text{rated}} = \frac{P_{\text{rated}}}{\omega_{\text{mrated}}} = \frac{r_b P_{\text{rated}}}{v_{\text{trated}}} \propto r_b^3 \propto P_{\text{rated}}^{3/2} \tag{4}$$

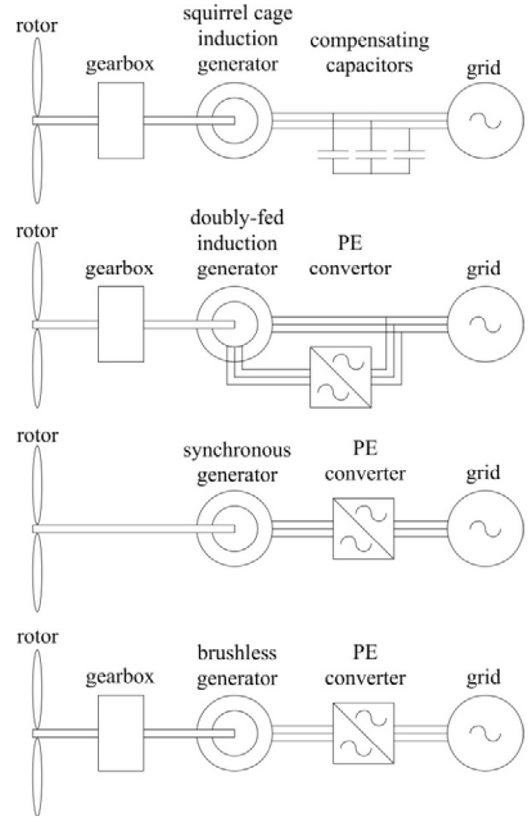

Fig. 2. Four commonly used generator systems [18].

where (1) was used in the last two proportionalities.

III. CURRENTLY USED GENERATOR SYSTEMS

The four most commonly used generator systems applied in wind turbines are shown in Fig. 2 and discussed below [13]–[18]. Table I lists the top 10 wind turbine manufacturers of 2012 [19] with the power levels of their products [20]–[29] and the generator systems they use.

A. Constant Speed Squirrel-Cage Induction Generator

During the last decades of the last century, most wind turbine manufacturers mainly built constant speed wind turbines with power levels increasing to ∼1.5 MW. This constant speed system consists of a three-stage gearbox and a squirrel-cage induction generator directly connected to the utility grid. This system (shown in Fig. 3) is also referred to as the Danish concept.

Above the rated wind speed, the power is mostly limited using the classic stall principle: if the wind speed increases above the rated wind speed, the power coefficient reduces, so that the power produced by the turbine remains approximately equal to the rated power. Sometimes active stall is used: negative pitch angles are used to limit the power.

The main strength of this system is that it consists of simple off-the-shelf components and that, therefore, it is cheap. Two variants of this system have been used to overcome some of its disadvantages.

TABLE I
TOP 10 WIND TURBINE MANUFACTURERS OF 2012, CURRENTLY USED GENERATOR CONCEPTS AND POWER RANGES [20]–[29]

Manufacturer	Concept	Rotor diameter	Power range
General Electric (US)	DFIG DD PM	77 – 120 m 113 m	1.5 – 2.85 MW 4.1 MW
Vestas (Denmark)	DFIG GFC PM	80 – 100 m 112 – 164 m	1.8 – 3 MW 1.8 – 8 MW
Siemens (Germany/Denmark)	GFC IG DD PM	82 – 120 m 101 – 154 m	2.3 – 3.6 MW 3 – 6 MW
Enercon (Germany)	DD EE	48 – 126 m	0.8 – 7.5 MW
Suzlon/REpower (India)	CS DFIG	52 – 88 m 95 – 97 m	0.6 – 2.1 MW 2.1 MW
Gamesa (Spain)	DFIG GFC PM	52 – 114 m 128 m	0.85 – 2 MW 4.5 MW
Goldwind (China)	DD PM	70 – 109 m	1.5 – 2.5 MW
Guodian United Power (China)	DFIG DD PM	77 – 100 m 100 m	1.5 – 3 MW 3 MW
Sinovel (China)	DFIG	60 – 113 m	1.5 – 5 MW
MingYang (China)	DFIG GFC PM	77 – 83 m 92 – 108 m	1.5 MW 2.5 – 3 MW

CS constant speed with gearbox and induction generator, possibly with two speeds or with extended slip
DFIG variable speed with gearbox, doubly-fed induction generator and partly rated converter
DD EE variable speed direct-drive synchronous generator with electrical excitation and full converter
DD PM variable speed direct-drive permanent-magnet generator and full converter
GFC PM variable speed with gearbox, permanent-magnet generator and full converter
GFC IG variable speed with gearbox, induction generator and full converter

1) Pole changing induction generators have two stator windings with different numbers of pole pairs so that the turbine can operate at two constant speeds to increase energy yield and reduce audible noise.
2) The semi-variable speed wind turbine has a wound rotor induction generator with an electronically variable rotor resistance. This enables larger speed variations and reduces mechanical loads and power quality problems. This system is sometimes mentioned as a separate generator system [15].

B. Doubly Fed Induction Generator

After 1996, many wind turbine manufacturers changed to a variable speed system with a doubly fed induction generator (DFIG) for wind turbines with power levels above roughly 1.5 MW. This system consists of a multistage gearbox, a relatively low-cost standard DFIG and a partly rated power electronic converter feeding the rotor winding. Pitch control limits the output power to rated power at wind speeds above rated.

The power rating of the converter is ~25% of the rated power, enabling a speed range from roughly 60% to 110% of the rated speed. This is sufficient for a good energy yield because the tip speed ratio can be kept optimal for a large part of the operating range.

Compared with the constant speed system, this system enables a more flexible match with requirements considering audible noise, mechanical loads, power quality, and energy yield. An important disadvantage of this system appeared when the grid codes of the power system operators prescribed grid-fault ride-through capabilities [2]. This was not possible with the standard DFIG system, and therefore a lot of work has been done to enable grid-fault ride-through [30]–[36]. This work has been so successful that general electric (GE), after changing to gear and full converter (GFC) systems around 2005, changed back to DFIG in 2012 [14].

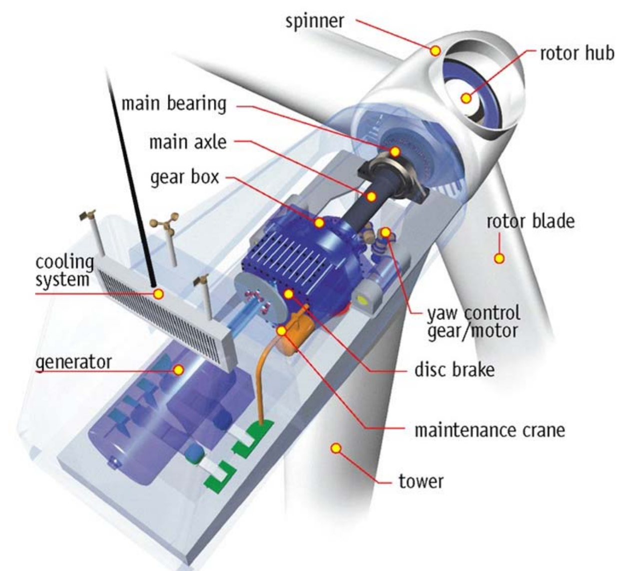

Fig. 3. Sketch of a nacelle with gearbox, in this case of a constant speed NEG micon wind turbine. Source: Bundesverband WindEnergie e.V.

C. Brushless Generator With GFC

Since around 2005, several large manufacturers have developed variable speed wind turbines with a gearbox, a brushless generator, and a converter for the full rated power. Pitch control limits the output power to rated power at wind speeds above rated. This system is mainly used to obtain better grid-fault ride-through characteristics than the DFIG and to avoid the maintenance and the failures of the brushes of the DFIG. However, a fully rated converter has more losses than a partly rated converter as in the case of a DFIG.

There are quite a number of variants of this system on the market because different generator types and different gearboxes are used. Several manufacturers use PM generators, but squirrel-cage induction generators are also used (Table I). The number of gear stages in this system may vary from one to three. According to (3), a lower number of gear stages implies a larger generator, but the resulting system may be more efficient and more reliable because of the omission of the high speed stage of the gearbox [17], [37]. The multibrid system shown in Fig. 4 has a single stage gearbox and a PM generator.

D. Direct-Drive Generator System

Since 1992, there have also been wind turbine manufacturers using gearless generator systems with direct-drive (DD) generators as shown in Fig. 5. The generator is a synchronous machine. A fully rated power electronic converter is necessary for the grid connection.

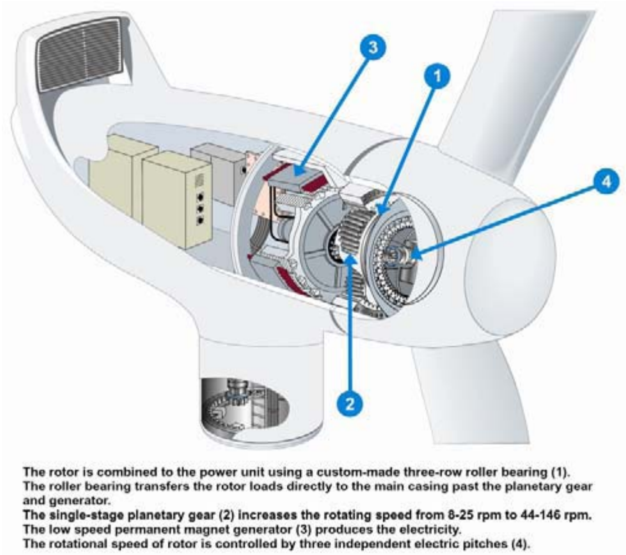

Fig. 4. Sketch of the multibrid system. Source: Winwind.

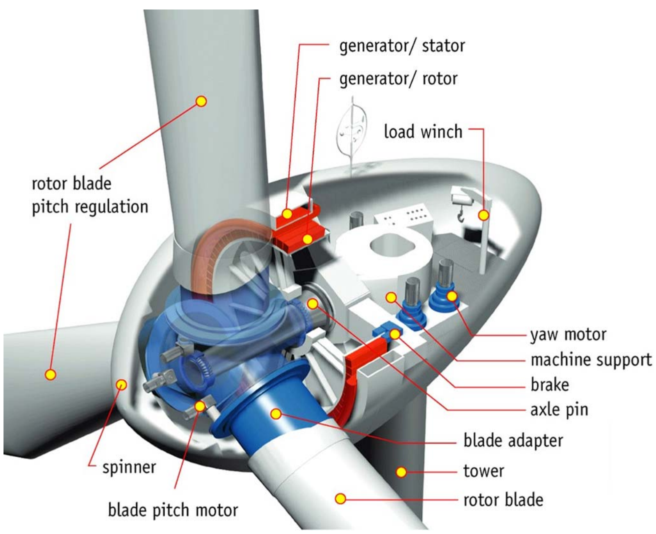

Fig. 5. Sketch of a gearless nacelle, in this case of an Enercon E-66 DD wind turbine. Source: Bundesverband WindEnergie e.V.

In the nineties, DD generators mainly had electrical excitation, because PMs were too expensive. When the price of PMs decreased, the focus shifted to PM generators. The high magnet prices around the year 2011 have again increased the interest in alternatives for PMs.

For a long time, Enercon has been the only large successful DD manufacturer, although there were several smaller DD manufacturers. However, also other large wind turbine manufacturers have started producing DD wind turbines (Table I).

The main reason for using DD systems is to increase reliability by avoiding the maintenance and the failures of the gearbox and by reducing the number of turbine parts. However, it has yet to be proven that the reliability of DDs is really better than that of geared systems [6].

The main disadvantages of the DD generator are that the low-speed high-torque generator (3) is a large, heavy, and expensive and that low speed generators are less efficient than high speed generators. Therefore, a lot of research has been done to optimize these machines. The electromagnetic and thermal limitations of the iron cored radial flux generators as applied in the industry are described in [10]–[12] and [38]–[40]. To reduce the manufacturing cost of DD generators, tooth wound concentrated windings have been proposed [41]–[43]. The additional losses due to the additional space harmonics are a point of concern.

E. Conclusion on Currently Used Generator Systems

It is clear that the constant speed system is disappearing. However, there is no clear convergence toward a single best wind turbine generator system, but instead the variety of wind turbine generator systems is increasing. The three currently used variable speed systems all have their strengths and weaknesses and are expected to remain the coming years. An attempt to compare these generator systems in terms of cost and energy yield was made in [17], but this comparison also did not result in a clear winner.

IV. Future Generator Systems

This section reviews elements of possible future generator systems, including hydraulic transmissions, alternative DD generators, brushless DFIGs, magnetic pseudo DDs, superconducting generators, and power electronic converters. For most of these systems, we are not yet able to predict if they will lead to a cost of energy lower than that of the currently used generator systems. Therefore, this paper describes proposed future generator systems and lists the critical advantages and disadvantages compared with the currently used generator systems.

A. Mechanical Continuously Variable Transmissions

Continuously variable transmissions make it possible to use directly grid connected synchronous machines with electrical excitation, thus avoiding power electronic converters.

The most commonly used mechanical continuously variable transmission is based on a gearbox with two output shafts [44], [45]. The main output shaft is connected to a constant speed generator. The speed of the other output shaft is controlled using a variable speed drive in such a way that the speed of the main shaft is kept constant. In a variant of this system [46], the variable speed shaft is mechanically connected to the constant speed shaft with a continuously variable speed transmission based on a metal belt.

To obtain a reasonable speed variation, the power level of the variable speed system must be considerable, comparable with the DFIG system. Furthermore, this system increases the complexity of the gearbox. Therefore, we do not yet see convincing advantages compared with the DFIG system.

B. Hydraulic Transmission Systems

Hydraulic transmission systems can be divided into hydrodynamic and hydrostatic transmissions [47]–[49]. The WinDrive (of Voith) is based on a hydrodynamic transmission or a torque converter, where turbines give energy to and take energy from an oil flow. This only works for high speeds, hence this system is combined with a gearbox. The drive trains of Wikov, ChapDrive, and Artemis (of Mitsubishi) are based on hydrostatic transmissions or positive displacement pumps, where cylinders displace pressurized oil. The Wikov system consist of a combination of a gearbox and a hydraulic system, while the gearbox is omitted in the systems of ChapDrive and Artemis.

Hydrostatic transmissions have the big advantages that they are significantly lighter and cheaper than gearboxes [47]. Furthermore, hydraulic transmission systems are normally used as continuously variable transmissions, hence a directly grid connected synchronous generator can be used, thus avoiding power electronic converters. However, hydraulic transmissions have not yet become commercially successful in wind turbines. Reasons are that the efficiency is lower than the efficiency of a gearbox, and that there is a risk of pollution with oil if something goes wrong. Because these systems have not yet been used on a reasonable scale in wind turbines, there is no data on the reliability of these systems. However, they are used in many other applications with low speeds and high torques, such as excavators and aeroplanes indicates the reliability can probably be made acceptable.

C. Alternative DD Generators

Reduction of cost, size, and weight of DD generators for wind turbines is an issue, especially at high power levels, because according to (4) the torque level increases more than proportional to the power level. Scaling functions illustrate this [50], [51].

To increase the shear stress, the use of transverse flux PM generators has been proposed [52]–[57]. However, until now the resulting shear stress of the DD generators in this application has not exceeded that of normal radial flux machines because of the relatively large air gap. Other disadvantages of these machines are the low power factor and the complicated construction due to the 3-D flux paths.

If the weight of DD generators is divided into electromagnetically active and structural material, the structural material is the heaviest part [38], [57]–[65]. Therefore, different methods to reduce the amount of structural material have been proposed.

The idea to use large diameter generators with an air core to remove the attractive force between stator and rotor [11], [38]–[60] has been adopted by, for example, Sway Turbine [61] (shown in Fig. 6), and Boulder Wind Power [62]. Along comparable lines, Goliath [63] uses a large diameter generator, but this generator seems to have an air-gap winding between the stator and rotor iron as described in [64].

Such constructions make it possible to use less electromagnetically active and structural material. However, protection of the windings and the magnets against the aggressive environment with humidity and salt is an issue.

In [11], [50], [51], and [65], it is proposed to reduce the distance between the bearings and the location of the electromagnetic forces using hybrid magnetic bearings or fluid bearings. Again, this enables the use of lighter constructions, but the bearings become more complicated.

Fig. 6. Picture of the large diameter DD generator of Sway Turbine. Source: Sway Turbine.

Fig. 7. Rotor of a brushless DFIG with six nested loops, as used in a machine with a stator with a four-pole and an eight-pole winding.

D. Brushless DFIG

In [66]–[72], it has been proposed to use the brushless doubly fed induction generator (BDFIG), also known as the brushless doubly fed machine, as a generator for use in wind turbines. The BDFIG has two stator windings, one of which is connected to the grid (the so-called power winding) and the other (the so-called control winding) is supplied via a converter, in the same manner as a DFIG. The machine has two principal fields, associated with the two stator windings, of different pole numbers which cross couple via the rotor. The rotor has a short-circuited winding consisting of so-called nested loops as shown in Fig. 7. The machine operates in a synchronous mode with a fixed ratio between shaft speed and the two stator frequencies, again like the DFIG.

The machine was proposed for wind turbine use around 1990 by a group at Oregon State University [68] and has been developed since then. The machine is not easy to analyze despite its simple construction and only recently more straightforward design procedures have emerged. Following the description of relatively small experimental machines [69], several larger machines have recently been built, including a 70-kW machine from Brazil [70], a Chinese machine rated at 200 kW and what is believed to be the largest machine to date namely a 250-kW machine built in the UK [67].

These larger machines demonstrate that the BDFIG can be built in larger sizes but a machine with a MW rating remains to be demonstrated. There are restrictions on the allowable pole

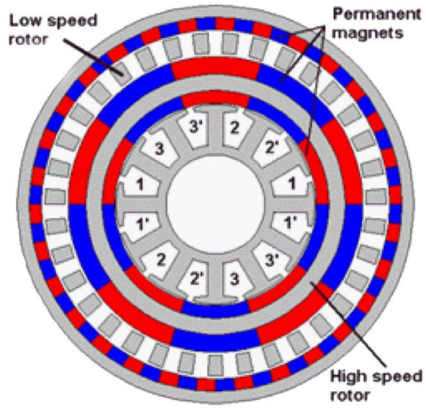

Fig. 8. Electrical machine accommodated in the bore of high-speed rotor of magnetic gear.

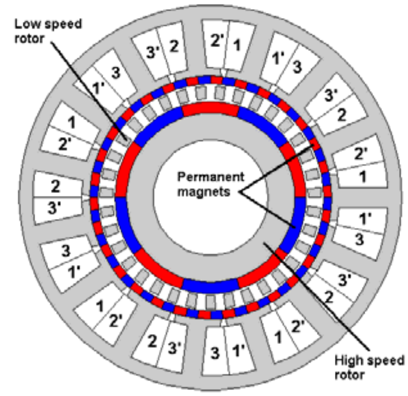

Fig. 9. PDD with magnetically and mechanically coupled magnetic gear and electrical machine.

numbers of the two principal fields, with the highest available natural speed (corresponding to the synchronous speed of a DFIG) with a 2-pole/6-pole combination being 750 rpm on a 50-Hz system. Therefore, the BDFIG is seen as a natural part of a medium speed drive with a natural speed in the order of 300 rpm. Research is in progress to develop this approach [71].

The BDFIG shares with the DFIG the benefits of low cost construction in that no PMs materials are used and only a fractionally rated converter need be employed. Simultaneously, the absence of brush-gear obviates one of the main failure modes of the DFIG. Use of the BDFIG therefore gives a low cost but reliable option [66]. The BDFIG also has a significantly improved LVRT performance compared with an equivalent DFIG, further reducing system cost and complexity [67]. Furthermore, it is a medium speed generator, which increases the efficiency and the reliability because the high-speed gear stage of the gearbox is avoided.

Compared with a DFIG of the same speed, a BDFIG has the advantages that it is brushless and that the LVRT capabilities are better and the disadvantage that it probably is slightly larger because of the additional winding.

E. Magnetic Pseudo DD Generator

A magnetic gear [73], [74] may be combined with an electrical machine to realise a high torque density magnetically geared drive in various ways. The simplest and the most obvious way are to mechanically couple an electrical machine to a magnetic gear as shown in Fig. 8.

Fig. 9, however, shows a pseudo DD (PDD) electrical machine, where the magnetic gear and the electrical machine are mechanically as well as magnetically integrated [75], [76]. The fundamental flux density component of the PMs on the high-speed rotor couples with the stator winding to produce torque, while the asynchronous space harmonic resulting from the modulation by the ferromagnetic pole pieces of the magnetic field of the high-speed rotor PMs couples with the PMs on stator to transmit torque at fixed gear ratio. When compared with the arrangement shown in Fig. 8, this topology facilitates access and cooling of the stator winding and simplifies manufacturing significantly, especially for large machines, since it only has two air gaps.

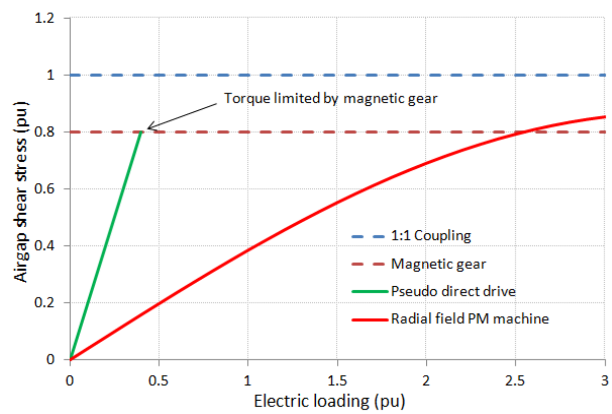

Fig. 10. Air-gap shear stress in PDD and radial field PM machines (electric loading of 1 pu corresponds to the thermal limit of a radial field PM machine).

The electromagnetic torque resulting from the interaction of the high speed rotor and the stator windings is similar to that of a conventional surface mounted PM machine. The magnetic gear increases this torque with the gear ratio G_r, which can exceed 10 in a single stage, and hence the torque density significantly increases. Fig. 10 shows a comparison between the typical air-gap shear stress in PDD machines and radial field PM machines. It can be seen that the torque produced by the PDD machines is limited by the magnetic gear element, and therefore, the PDD machine would be more suitable for applications where the peak torque is not significantly higher than the rated torque, such as wind power generation. It can also be seen and due the inherently low electric loading, a PDD machine can operate continuously at its peak torque capability.

Prototypes of magnetic PDD machines have been designed and tested for various applications. A PDD machine with a continuous torque output of 4 kNm has been tested, and prototype with a torque output of ~20 kNm is currently going through the initial testing phase. However, development is in progress to increase torque to magnitudes required for wind turbines. Fig. 11 shows a design of a PDD generator for a 3-MW wind turbine, and because of the inherently low electric loading, Fig. 11, its rated efficiency is >98%. On the other hand, the total mass of generator, including the structural components, is only 35 tons, and the overall

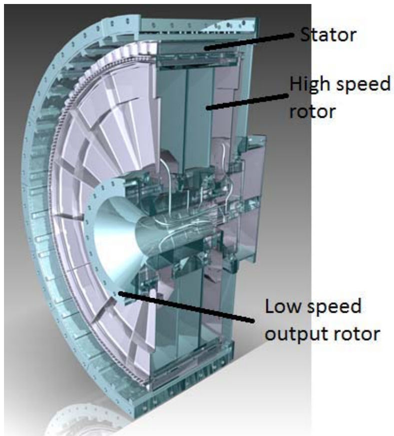

Fig. 11. 3-MW, 15-rpm PDD generator for a wind turbine (courtesy of magnomatics limited).

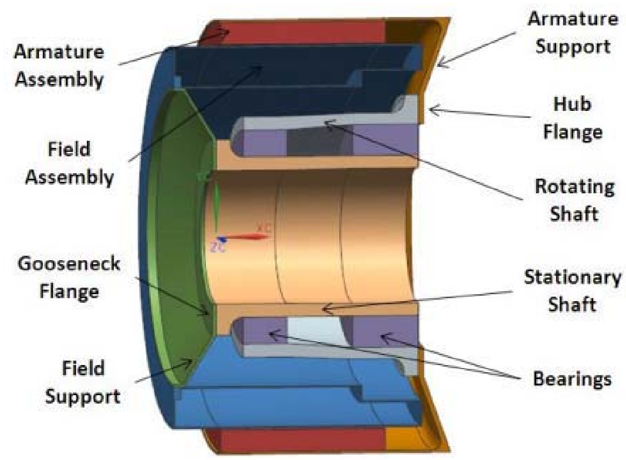

Fig. 12. Proposed 10-MW LTS wind turbine generator from GE. Reproduced from [78].

diameter is 3.8 m. Therefore, it is anticipated that the size/mass of PDD generator would be <50% of the size/mass of PM DD generator. However, although the quantity of PMs in a PDD machine may be higher, this can be significantly reduced by appropriate optimization. This is subject of further research.

Summarising, the most important advantages of the PDD are the anticipated reduction of weight compared with DD generators, and the significant reduction of maintenance compared with mechanical gearboxes. The most important disadvantage is the large amount of PM material.

F. Superconducting DD Generators

Superconducting machines have been proposed for wind turbines by both industry [77]–[79] and academia [80]–[85], due to their potential for high torque density and efficiency. Superconductors exhibit almost zero dc resistance and are therefore commonly proposed for field windings in wound field synchronous generators. With a vanishing dc resistance, the resistive losses will be suppressed and the field current can be increased such that air-gap flux densities of 2–3 T can be achieved. Therefore, superconducting machines have very high torque densities. Using (3), the volume of a superconducting machine can be reduced by a factor of 2–3 compared with a traditional machine with an air-gap flux density just below 1 T.

If the current density, J_{Cu}, on the stator is kept constant as the machine is reduced in size, the copper losses, P_{Cu}, will be proportional to the volume of copper, V_{Cu}, and hence will reduce as the machine becomes smaller in size

$$P_{\mathrm{Cu}} \propto J_{\mathrm{Cu}}^2 V_{\mathrm{Cu}}. \tag{5}$$

This leads to an increased efficiency for the superconducting machine compared with traditional machines.

There are three categories of superconducting wires: 1) low temperature superconductors (LTSs) with critical temperatures below $T_{\mathrm{C}} < 18$ K; 2) high temperature superconductors (HTSs) with $T_{\mathrm{C}} < 110$ K; and 3) $\mathrm{MgB_2}$ discovered in 2001 with $T_{\mathrm{C}} < 39$ K intertwined between LTS and HTS. Although employing superconductors in wind turbine generators can lead to attractive advantages, they currently come with substantial uncertainties and challenges. Superconductors only

Fig. 13. Proposed 10-MW HTS wind turbine generator from AMSC. Reproduced from [79].

remain superconductive as long as their operating point is kept within three interdependent limits; namely critical current density, critical flux density, and critical temperature $\mathrm{T_C}$. Because of this LTS is commonly operated at 4 K, $\mathrm{MgB_2}$ at 15–20 K, and HTS at 30–50 K.

LTS has been proposed by GE for a 10-MW DD wind turbine [78], Fig. 12, where the LTS field winding is stationary and the armature winding rotates with slip rings. LTS is commercially available at relatively low cost for the MRI devices and GE suggests to transfer the MRI technology to the wind turbines. However, as the operating temperature needs to be kept at 4 K the machine would require a complex cooling system and thermal insulation, which to date has deterred all LTS machined development.

HTS has been proposed by American superconductor (AMSC) for a 10-MW D Dwind turbine [79], Fig 13. HTS has the advantage that the cooling system and thermal insulation can be relatively simple, where the cryocoolers can be purchased off-the-shelf. On the downside HTS is expensive and is currently not available in sufficient lengths for commercial roll-out.

$\mathrm{MgB_2}$ has been proposed by advanced magnet lab (AML) in a fully superconducting 10-MW DD wind turbine [81],

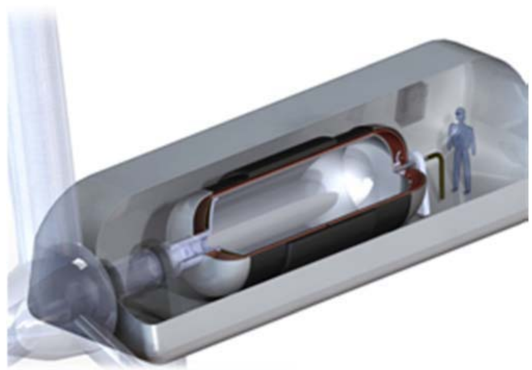

Fig. 14. Proposed 10-MW MgB_2 wind turbine generator from AML. Reproduced from [81].

Fig. 14, where both armature and field windings are superconducting. This implies that the superconductor will carry alternating current, which results in large losses in the superconductor and consequently large requirements for cooling power. These losses could be limited by further development of MgB_2 wires with very small filaments, but currently no MgB_2 conductor is ready for alternating current at high fields. MgB_2 wire is commercially available at a relatively low price if the flux density is kept at 1 T. However, if the field is increased to 3 T the price becomes comparable with HTS at similar flux densities and temperatures [81]. MgB_2 requires an operating temperature of 15–20 K and would therefore also require sophisticated cooling systems and thermal insulation.

To summarize, there are three different types of superconductors and all three have been proposed for future 10-MW wind turbines. None of these have been built or demonstrated yet. For other applications, such as ship propulsion, superconducting machines have been built and tested [83]–[85], but they have not yet become a commercial success. This shows that the area of superconducting wind turbine generators is very far from standardization and all paths are still open to be explored.

G. Power Electronic Converters

In variable speed wind turbine generator systems with partly or fully rated converter, mostly the standard back-to-back voltage source inverter is used, both for DFIG systems and for systems with a full converter [30]–[36], [86]–[88].

This system needs more than one conversion stage to convert the frequency and the voltage level making it compatible to the grid voltage, as is shown in Fig. 15. The growing power rating is accompanied by the need to increase the voltage on the dc link between the back-to-back converters. A typical value would be 5 kV for a 3.3.kV primary side grid voltage. To handle these voltages multilevel converters are needed.

The further evolution of wind power systems will be largely driven by reliability considerations [3]–[9], which implies that mature multilevel converters such as the three-level neutral point clamped topology would be favored. The choice of suitable converter topologies and further development of power electronic devices and device packages will be largely driven a better understanding of failure mechanisms and

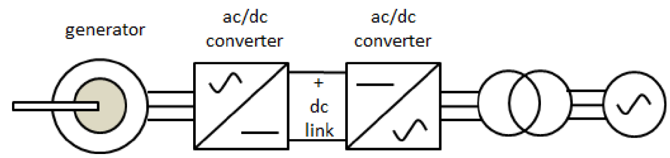

Fig. 15. Overview of the power conversion components.

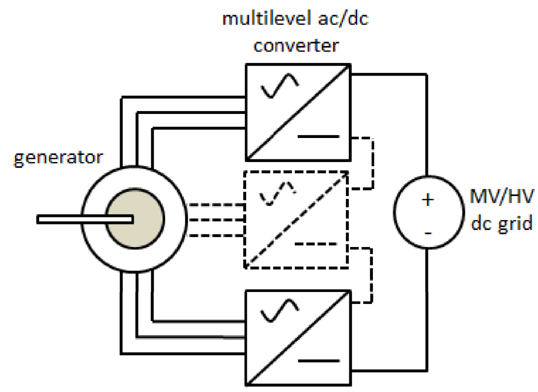

Fig. 16. Generator–converter modular multilevel system.

thermal cycling considerations. Especially, the generator side converter is badly effected by the temperature cycle behavior and nonlinear factors of the wind loading such as turbulence and gusts [89]. In DFIG and superconducting DD systems, the situation is aggravated because power electronic converters handle ac frequencies that can be in the order of or below 2 Hz, which is comparable with the thermal times constants of the device packages.

1) Modular Fault Tolerant Conversion Systems: A high power converter needs a large number of semiconductor devices and is complicated. This potentially increases the risk of failures. However, if measures can be taken to allow safe failures then the availability of the system operation can be assured. Modular converters are attractive candidates when failed units can be bypassed.

In a number of studies, transformerless designs were investigated that are based on the modular multilevel concept for high voltage conversion [90]–[92]. The intermediate dc link is eliminated and it is proposed to directly generate an output ac or dc voltage in the 10–100-kV range. An attractive feature is that in offshore wind parks the wind turbines can be connected directly to a MVDC or HVDC collection grid.

In Fig. 16, a schematic of such a modular multilevel system is shown. The generator is divided into a number of segments, each of which behaves as a three phase or single phase generator on its own. The segments carry the stator windings, which are electrically isolated from the other winding segments and the stator core. An active rectifier module converts the ac to dc and the units are strung up in series.

Fault tolerance needs to be achieved both in the machine segment and power electronics module. Electrically a module can be bypassed, but it is also necessary to ensure that a winding fault does not cause overheating or creates an undesired breaking torque. The power electronics converter and the machine segment design should incorporate failure

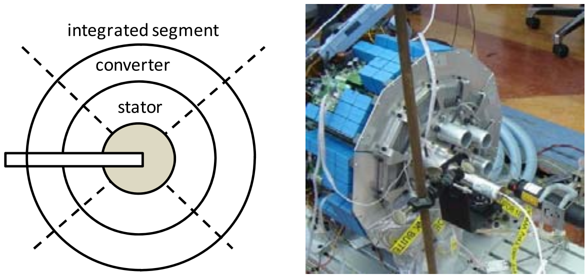

Fig. 17. Segmented fault tolerant generator–converter system.

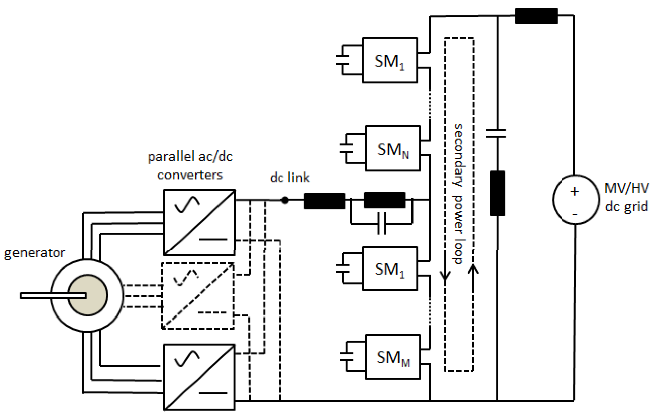

Fig. 18. Transformerless modular multilevel converter with dc link [98].

mode, high voltage and thermal engineering solutions using some of the principles described in [93] and [94]. The power converter and machine segments are physically integrated and the large reactance of the concentrated stator windings limits the current to 1 PU when a short-circuit occurs [94]. A schematic and a photo of the system are shown in Fig. 17.

2) DC Link Transformerless Generator System: The generator-converter multilevel modular system puts high demands on the high voltage isolation of the windings of the machine, especially the ground wall isolation. Initial studies, [95], [96] need to be followed up by detailed designs and validation on experimental systems. Meeting the isolation requirements of the large common mode voltage and capacitive coupling effects due to switching dv/dt's could be a daunting high voltage engineering challenge. Furthermore, the torque produced by the generator will be compromised due to the reduced copper fill factor in the slots due to the volume of isolation material that needs to be added. The thermal resistance of the windings will also be affected by the isolation material reducing the current density in the conductors. For this reason, we prefer solutions that use dc link voltages that are compatible to existing isolation voltage classes for stator windings, as used in high power drives [97].

Based on typical voltages used in high power drives, a practical dc link voltage of 1–10 kV should be realistic using current technology. The voltage is then stepped up to MV/HVDC using a dc step-up converter as shown in the system schematic in Fig. 18. It is proposed that the modular multilevel dc converter concept described in [98] is used since it is transformerless and shares the fault tolerance by redundant modules feature with other modular multilevel converters. A unique feature of this converter is a secondary power loop that cycles power between the modules using the principle that power at different frequencies are orthogonal to each other.

V. Conclusion

There is no convergence toward a single best wind turbine generator system, but instead the variety of wind turbine generator systems is increasing. The three currently used variable speed systems (with gearbox and DFIG, with gearbox and full converter and DD) are expected to remain for the coming years. Hydraulic transmissions enable continuously variable transmission and are significantly lighter than gearboxes, but their efficiency is lower. A brushless DFIG is a medium speed generator without brushes and with improved LVRT characteristics compared with the DFIG. Magnetic PDDs are smaller and lighter than DD generators, but need a sufficiently low and stable magnet price to be successful. Also superconducting generators can be smaller and lighter than normal DD generators, but both cost and reliability need experimental demonstration. In power electronics, there is a trend toward reliable modular multilevel topologies.

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