Electrical Generator Technologies for Offshore Wind Turbines

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Abstract

In this chapter different electric generator topologies for offshore wind turbines will be reviewed. Although, the most common generator type used in the onshore wind turbines is the doubly-fed induction generator, different generator designs are proposed for large offshore wind turbines, which operate in harsher conditions and difficult to maintain. Some of these designs are direct-drive permanent magnet generators, hydraulic power take-off systems and superconducting generators.

Keywords: electrical generators, direct-drive systems, permanent-magnet generators, hydraulic power take-off, superconducting generators.

Introduction

The mechanical energy captured by the turbine blades are converted to electrical energy and is fed into the grid with a series of components such as; gearbox, generator, power electronics, transformer and transmission. Generator is the most important component in the power take-off system and there are many different generator types that can be used in turbines depending on the size, operating conditions, and speed range. Some generator types used in commercial wind turbines are presented in Table 1.

There is a trend toward higher power-rated turbines, which help to reduce the installation and maintenance costs per kilo-watt-hour [1]. The power rating of the turbines increased by 100 times since 1985 and this trend seems to continue. The onshore wind energy market is considered to be quite mature and the power rating is not expected to go beyond the present

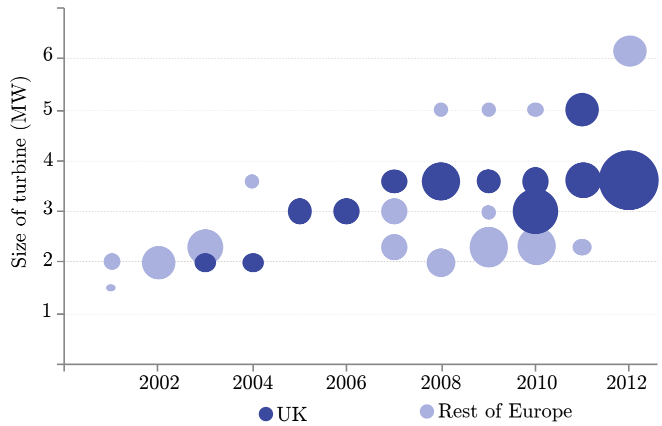

Figure 1: Commercial offshore wind farms turbine size for UK and Europe. Bubble size is proportional to the wind farm rated output [2].

3–3.6 MW size due to transportation limitations. However, large offshore wind turbines can be assembled in port and transported in one piece.

In Figure 1, the turbine power ratings for commercial offshore wind farms across the UK and the rest of Europe are presented. The power rating of the offshore wind turbines increased from 2 MW to 5 MW in the last decade. In [3], it is predicted that in 2020, 85% of the offshore wind turbine installations are expected to be larger than 5 MW. However, there are problems associated with larger wind turbines. In a recently completed EU project (Up-Wind), it is stated that the excessive top-head mass is one of the most critical issues for very large wind turbines [4]. If the tower-head mass is reduced, significant savings can be made in the structural, foundation and installation costs. A smaller, lighter generator also enables the nacelle to be transported and lifted to the tower in one piece, which reduces the installation time.

Another critical issue is the reliability of the power take-off systems. Offshore wind turbines operate in a harsher environment compared to onshore wind turbines. Furthermore, access to offshore wind turbines is much more difficult and any repair is subject to the weather and the sea conditions. Especially, in winter it may take weeks to find a suitable window for maintenance. If a crane is required for a major replacement, it is also subject to the availability of appropriate vessels. All these factors add weeks or even months of lost energy income on top of the repair cost.

The advantages and disadvantages of some generator systems have been tabulated in Table 2. In the following sections, conventional generator topologies presented in Table 1 and a few other novel generator concepts will be investigated.

Drive Train	Generator	Power	Rotor	Rated	Manufacturer
Multiple Stage Gearbox	DFIG	2 MW	90 m	20.7 rpm	DeWind
	DFIG	2 MW	90 m	19 rpm	Gamesa
	WRIG	2 MW	88 m		Suzlon
	PMSG	2 MW	88 m	16.5 rpm	General Electric
	DFIG	2.5 MW	90 m	14.9 rpm	Nordex
	DFIG	3 MW	100 m	14.3 rpm	Ecotecnia
	DFIG	3.6 MW	104 m	15.3 rpm	General Electric
	DFIG	4.5 MW	120 m	14.9 rpm	Vestas
	DFIG	6 MW	126 m	12.1 rpm	RePower
Single–Stage Gearbox	PMSG	3 MW	90 m	18 rpm	Winwind
	PMSG	5 MW	116 m	14.8 rpm	Multibrid
Hydraulic Transmission	EESG	2 MW	90 m	20.7 rpm	DeWind
	EESG	2.4 MW		10 rpm	Mitsubishi
Direct-Drive	PMSG	1.5 MW	77 m	17.3 rpm	Vensys
	EESG	1.6 MW	78 m		MTOI
	PMSG	2 MW			Mitsubishi
	PMSG	2 MW	71 m	23 rpm	Zephyros
	PMSG	3 MW	101 m	14.4 rpm	LeitWind
	EESG	4.5 MW	114 m	13 rpm	Enercon
	EESG	7.5 MW	127 m	11.7 rpm	Enercon

Table 1: Drive train types of some commercial wind turbines [5, 4].

	Multi-Stage Gearbox		Single-Stage Gearbox		Direct-Drive	
	DFIG	Hydraulics	DFIG	PMG	PMG	EESG
Mass	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star$
Size	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star$	$\star$
Efficiency	$\star$	$\star\star$	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$
Reliability	$\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star\star$	$\star\star\star$
Cost	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star$	$\star$

Table 2: Comparison of different power take-off systems.

1 Doubly-fed Induction Generator

Doubly-fed induction generator coupled with three-stage gearbox (DFIG-3G) is the most common power take-off system in wind turbines, with more than half of the market share. Some of the wind turbine companies that use this configuration have been presented in Table 1. DFIG generators are usually coupled with multi-stage gearboxes to increase the rotational speed. DFIGs rotational speed is close to the synchronous speed (e.g. 1500 rpm for a 4-pole machine in a 50 Hz grid). In Figure 3 one of the largest DFIG wind turbines(6 MW) are presented, which are manufactured by RePower.

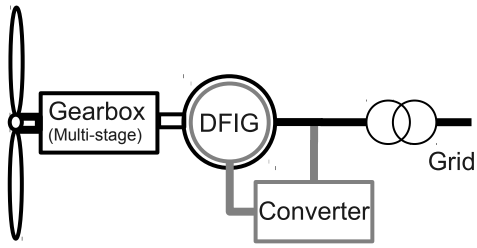

Figure 2: Doubly-fed induction generator coupled to multi-stage gearbox.

Doubly-fed induction generator is a special type of induction machine. DFIGs differ from squirrel-cage induction generators as they need wound-rotor and electrical brushes. The frequency of the armature voltage is controlled by the field winding. Armature winding of the doubly-fed induction generator is directly connected to the grid. Therefore, DFIGs do not require full-rating power electronics, which is the main advantage of this generator type. The rating of the converter is about 25–30% of the generator capacity, which reduces the overall cost [6]. The advantages of the DFIG system can be listed as;

- Partially rated power electronics reduces the cost.
- Ability to supply reactive power to the grid.
- Off-the-shelf components, wide range of generator options.

However, DFIGs also have a few disadvantages [6]:

- A multi-stage gearbox is necessary which may cause reliability issues.
- A slip ring is used, which require regular maintenance.
- High torque peaks in the machine and large stator peak currents under grid fault conditions. The power electronics should be protected.
- In case of grid disturbances, the ride-through requirements make the DFIG control complex.

Figure 3: RePower 6 MW wind turbines with DFIG (Courtesy of RePower, Jerome a Paris).

2 Direct Drive

In direct-drive systems, the generator is directly connected to the turbine, therefore the generator speed is very low (usually in the range of 10–20 rpm) and the torque requirements are very high, which results in very large and heavy generators. The large diameter of direct-drive generators increases the support structure mass. Furthermore, the airgap clearance in direct-drive generators are bigger than conventional generators due to manufacturing tolerances.

The advantages of direct drive generators are simplified drive train and higher efficiency (especially at partial loads) [6]. The absence of gearbox reduces the maintenance requirements and increases the reliability. Two types of generators are generally used in direct-drive power take-off systems: electrically excited synchronous generators and permanent magnet generators.

2.1 Electrically-Excited Synchronous Generators

Schematic of an electrically excited synchronous generator is presented in Figure 4. This type of generator is used in Enercon wind turbines. Enercon E-136 generator (see Figure 5), which is 10 m in diameter and weights 220 tones, is one of the largest wind turbine generator.

Direct-drive electrically excited synchronous generators are similar to conventional synchronous generators with high number of poles to compensate for the low rotational speed. The generator has a wound rotor winding, which requires slip rings to excite. The reactive power and generator output voltage can be controlled using the field current. The assembly is easier compared to permanent magnet machines as there is no magnetic attraction between rotor and stator. Rare-earth permanent magnets are not used in the

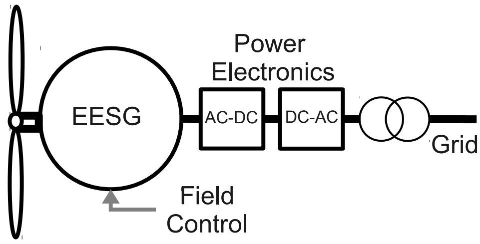

Figure 4: Direct-drive electrically excited synchronous generator.

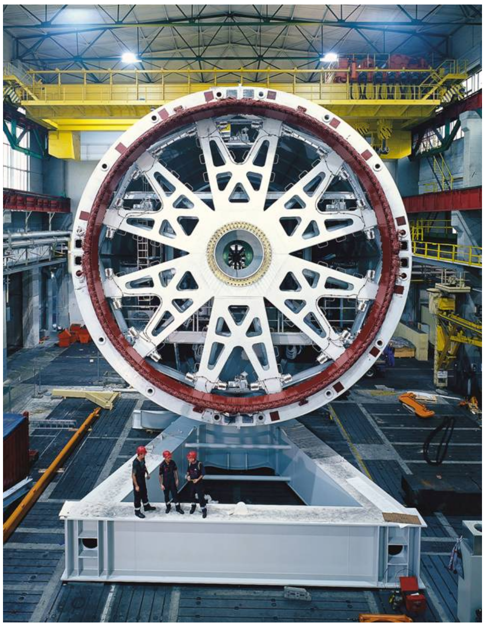

Figure 5: Enercon E-126 7.5 MW, 13 rpm direct-drive electrically excited synchronous generator (Courtesy of Enercon).

generator, so the cost is lower than PM generators. The disadvantages of the EESGs can be listed as:

- Largest and heaviest generator type.
- Slip rings require regular maintenance.
- Losses in the field winding reduce efficiency.

2.2 Permanent Magnet Generators

Direct-drive permanent magnet generators are synchronous generators that have rare-earth magnets instead of a field winding. They became popular in the recent years due to simple and robust structure. In Figure 6, schematic of a DDPMG is presented. In Figure 7, a 3.8 MW 21 rpm DDPM generator is shown, which is manufactured by the Switch. The generator is mounted directly between nacelle and the blade hubs.

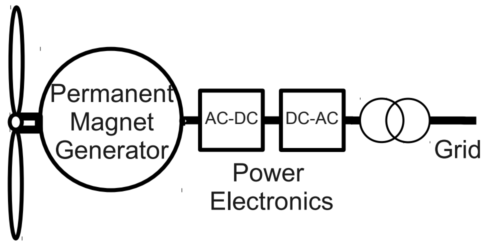

Figure 6: Direct drive permanent magnet generator.

Compared to geared solutions and electrically excited synchronous generators; direct-drive permanent magnet generators have the following advantages:

- The generator has no slip rings, which require regular maintenance.
- Having no field winding losses, the generator has a better efficiency.
- PM generators usually have higher torque densities.

However, the drawbacks of the permanent magnet generators can be listed as:

- Iron-cored DDPMGs are difficult to assembly due to attraction force between rotor and stator.
- Increased cost due to high price of rare-earth permanent magnets.
- Risk of demagnetization of magnets during short-circuit faults.
- No control over the induced voltage magnitude.

The biggest drawback of permanent magnet generators is the high cost of rare-earth magnets, which has increased more than tenfold between 2009 and 2011 due to export and mining regulations introduced by China [7]. In Figure 8, the price variation of Neodymium Oxide is presented. Although the prices of permanent magnets came down after the peak in 2011, they are still volatile and still four times more expensive compared to five years ago. It is stated in [8] that the future DDPMGs are in risk due to high demand of rare-earth metals and supply chain problems due to political risk.

There are a few permanent magnet topologies that aim to achieve higher torque densities. One of the best candidates is the transverse flux permanent magnet (TFPM) machine. In a TFPM machine the winding space can

Figure 7: 3.8 MW, 21 rpm direct-drive permanent magnet generator and installation to the nacelle (Courtesy of The Switch and Dongfang Electrical Machinery).

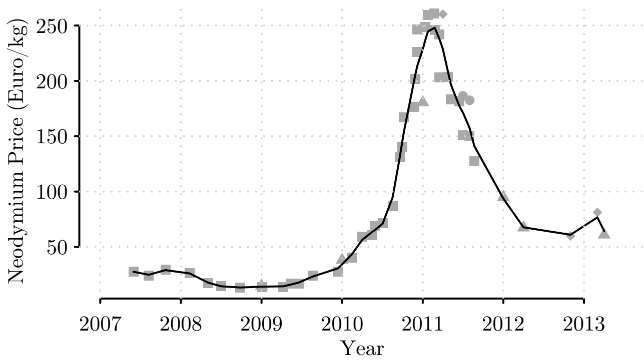

Figure 8: Neodymium Oxide price variation between 2007 and 2013 (data points obtained from Peak Resources Ltd and Lynas Corp.).

be increased without decreasing the available space for the main flux [9]. Thus, the machine can have a short pole pitch which helps to increase the frequency and magnitude of the induced voltage at low rotational speeds. In [9], different TFPM machine topologies are summarised. It is stated that, a 5 MW TFPM machine is 25% lighter than a conventional PMG. In general, TFPM machines have simple windings and higher torque densities. On the other side, the flux path is more complex making the mechanical design and manufacturing more complicated [1, 10].

3 Generators with Single Stage Gearbox

Direct-drive generators have many advantages compared to geared generators. The most obvious one is the higher availability and reduced maintenance costs. However, direct drive generators are large and heavy. The middle road between direct drive generators and high speed generators is a hybrid solution with a single-stage planetary gearbox and a medium-speed generator [11]. The generator can be a permanent magnet generator or a doubly fed induction generator. A medium-speed generator reduces the cost compared to a direct-drive generator. Moreover, the high-speed stage of the gearbox, which is considered to be the least reliable section, is eliminated.

The idea was first introduced by Multibrid of Germany. This concept has gained much attention because it has lower generator cost than the direct-drive concept, and the lower-gear box cost, higher availability and operating reliability than the multiple-stage geared drive concept. In summary, the advantages of the single stage gearbox concept are;

- Reasonable overall reliability. The low-speed gear stage is more reliable than multiple-stage gearboxes.
- Decreased generator mass and cost compared to direct-drive systems.
- Higher utilization of magnetic materials with increased rotational speed.

Thus, by accepting a small risk on the gearbox side high mass and high cost of the direct-drive systems can be mitigated [12]. Areva Multibrid 5 MW turbine (see Figure 9) has an integrated gearbox and generator design. The turbine has a single main bearing and has no main shaft. By this way, the nacelle mass is reduced and possible bearing problems are minimized.

Figure 9: Areva 5 MW Multibrid wind tutbine with combined gearbox and geratator (Courtesy of Areva).

4 Novel Generator Systems

There are also some novel generator concepts that aim to eliminate the problems of the existing topologies such as high tower mass, reliability or regular maintenance requirements. These problems arise especially for turbines larger than 5 MW. Although there are not proved commercial products for these generator types, they may become popular in the following years as the average size of the offshore wind turbines continue to increase.

4.1 Hydraulic Power Take-off Systems

Hydraulic transmission systems are proposed to drive the generator at synchronous speed regardless of the wind turbine speed. Thus, the generator can be directly connected to the grid eliminating any power electronics. There are two main concepts as presented in Figure 10. In the first configuration, a gearbox is used to couple the hydraulic transmission system, where in the second configuration, there is no mechanical gearbox and the hydraulic pump is directly coupled to the turbine. The output speed of the hydraulic transmission is controlled to keep the generator speed constant.

Voith Turbo designed a 2 MW wind turbine hydraulic transmission system, which is presented in Figure 11. A conventional synchronous generator is directly connected to the medium-voltage grid without intermediate electrical stages such as power electronics and step-up transformer. The absence of power electronics and transformer means reduced cost and increased reliability.

Artemis Intelligent Power designed a digital controlled hydraulic transmission system, which ensures fast response and efficient operation. Artemis Intelligent Power is designing a 7 MW hydraulic power take-off system, which has a digital displacement pump that drives two independent hydraulic motors and two synchronous generators. Double generator configuration introduces redundancy in the system. Thus, even if one of the generators fails the other one can continue to operate until the next maintenance. Furthermore, at partial loads one of the sets can be idled to increase the overall efficiency.

The weak point of a hydraulic system is the fault ride through capability. Since there are no intermediate stages between generator and the grid, in case of a grid-fault the control loop of the hydraulic system should be fast enough to respond within grid requirements. Although, mechanical control systems may not be fast enough, Artemis Intelligent Power's electronically controlled hydraulic valves decrease the reaction time of the system. In [13], it is claimed that a control bandwidth up to 20 Hz is achievable.

4.2 Generation at Sea Level

High tower head mass is problematic for large offshore wind turbine, especially for floating wind turbines. A nacelle that weights several hundred tonnes may introduce stability issues and increases the installation cost. The tower head mass can be reduced by placing the electrical generator at sea level. This also means easier access to some critical components. The response time of the hydraulic pump and hydraulic motor should be fast enough to satisfy the fault-ride-through requirements of the grid.

ChapDrive is developing a 5 MW hydraulic power take-off system for offshore wind turbines [14], in which the hydraulic motor and the generator is placed at ground level, inside of the tower. The nacelle mass of the turbine is expected to be less than 200 tonnes. University of Delft, applies the same hydraulic concept with a small modification in the We-at-Sea project [15]. Instead of using individual generators for each turbine, they propose to use a central generator unit(see Figure 12) for all the turbines in the farm. Sea water can be used to transfer energy from turbines to central generation unit. This unit can be placed on shore for near off-shore wind turbines.

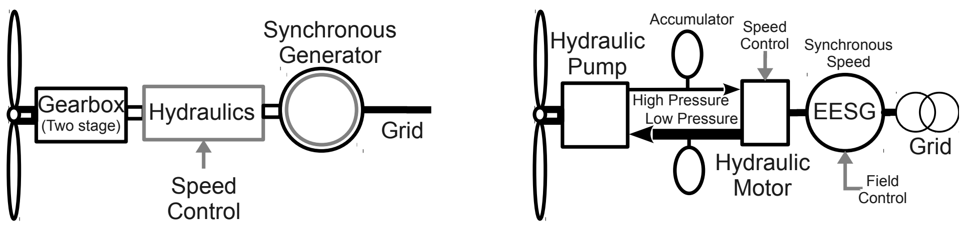

Figure 10: Hydraulic system coupled with two-stage gearbox and synchronous generator and power take-off system with hydraulic transmission and synchronous generator

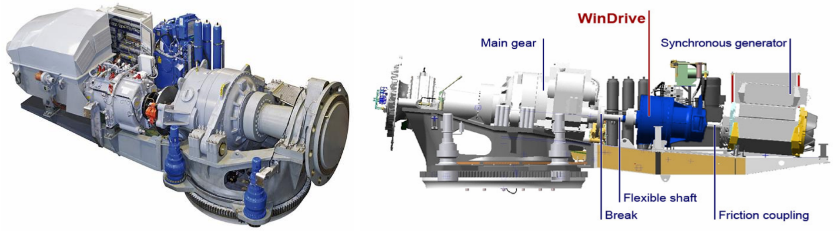

Figure 11: Windrive 2 MW power take-off system with hydraulic transmission (Courtesy of Voith Turbo).

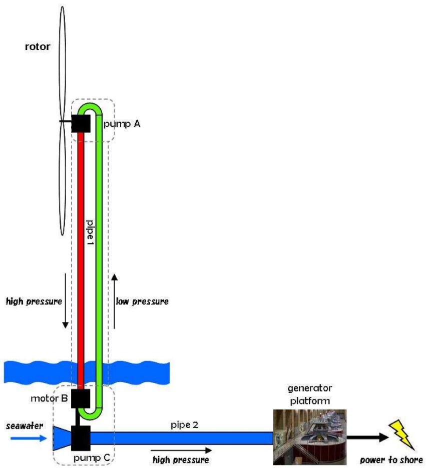

Figure 12: Schematic of the seawater-based hydraulic power take-off system [15].

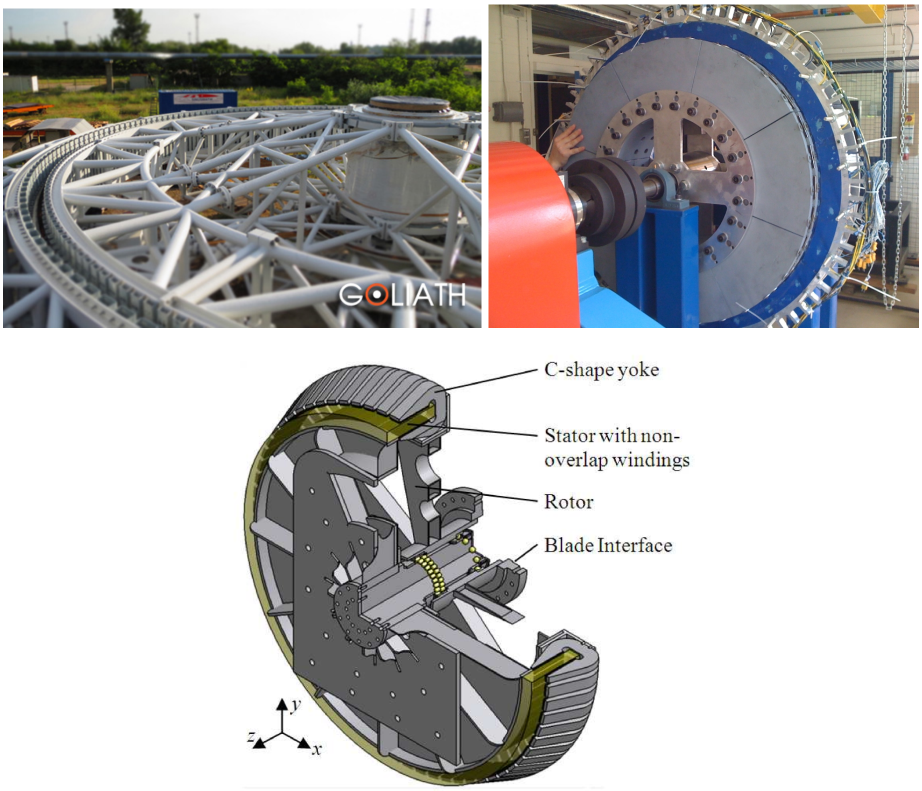

Figure 13: Air cored permanent magnet generators: 3 MW radial flux PM generator (Courtesy of Goliath Wind), 25 kW axial flux PM generator (Courtesy of NGenTec), 300 kW radial flux PM configuration [18].

4.3 Ironless Permanent-Magnet Generators

Electrical steel laminations are used in the stator and rotor core of conventional permanent magnet generators. The electrical steel has a low magnetic reluctance, however, the assembly and repair of an iron cored permanent magnet generator is very difficult due to high magnetic attraction forces between rotor and stator. Furthermore, a heavier support structure is required to keep the airgap clearance constant and non-balanced forces reduce the lifespan of the generator bearings. These forces can be eliminated with an air cored stator winding design [16]. The elimination of these forces reduces the structural mass considerably as described in [17]. Also, the machine can be assembled and maintained much easier.

As an additional advantage, several axial flux permanent magnet machines can be stacked in the axial direction. Thus, each machine can operate independently and the faulty section can be disconnected from the rest of

Figure 14: YASA (yokeless and segmented armature) motor, 750 Nm (Courtesy of YASA Motors).

the machine. Thus, the machine can operate at partial load until the next maintenance.

The disadvantages of air cored permanent magnet generators can be listed as;

- Increased magnet mass and cost compared to iron cored PMGs.
- Lower air-gap flux density.
- Heat transfer from coils is reduced. Additional cooling system may be required.

Instead of electrical steel laminations, soft magnetic composites (SMCs) can also be used. SMCs can be manufactured in complex shapes, giving more freedom and modularity in the machine design. A spin-out company from University of Oxford: YASA (yokeless and segmented armature) motors utilized SMCs in their PM motor, which is presented in Figure 14. The motor, which has a forced oil-cooling system, is primarily designed for electric cars. It has a high efficiency and torque density but the performance and total mass of this machine is not clear for large diameter, low-speed applications.

4.4 Pseudo Direct Drive (Magnetic Gears)

In pseudo direct drive system, the generator is coupled to prime-mover with an intermediate magnetic transmission. The generator can be integrated with the gearbox as shown in Figure 15. Thus, the input shaft can be connected directly to the slow-rotating turbine, while the generator rotates at a higher speed. By this way, the size of the generator can be significantly reduced without using mechanical or hydraulic transmission systems.

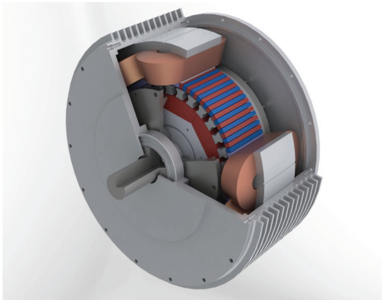

Figure 15: Combined magnetic gearbox and generators (Courtesy of Magnomatics).

The magnetic gears are contactless, lubricant-free and have no friction. Thus, magnetic transmission offer higher efficiency and reliability compared to geared systems. In a magnetic gear, the generator is not directly coupled with the prime mover; the vibrations are not transferred to the generator side and if the input torque exceeds the maximum torque, the magnetic gears just decouple from the prime mover. This is advantageous for some cases, but it also limits the fault-ride-through capabilities of the system.

Magnomatics, which is the leading company in magnetic transmission systems, designed magnetic gears for electric car motors and ship propulsion systems. They are also planning to manufacture pseudo direct-drive systems for wind turbines.

4.5 Superconducting Generators

Superconducting electrical machines have drawn interest since the discovery of the first superconductors in 1911, but it was after the discovery of high-temperature superconductors that the research on the applications of superconductivity has been boosted. Superconducting machines operate at higher air-gap flux densities due to the higher MMF created by superconducting wires that can conduct 100 A/mm^2 compared to 5–6 A/mm^2 of a copper coil. Thus, they have higher power densities than conventional electrical machines and reduce the size significantly. In [19], it is proposed that HTS machine can reduce the mass and volume by 40–50%. In Figure 17, the size and mass comparisons between superconducting machines and conventional motors are presented. In Figure 17, a 36.5 MW superconducting ship propulsion motor is compared with a conventional motor. The superconducting motor delivers 50% more power in less than half of the mass of the conventional generator.

Data from direct-drive systems have been collected to compare mass to torque ratio of HTS machines with other type of generators. The result is

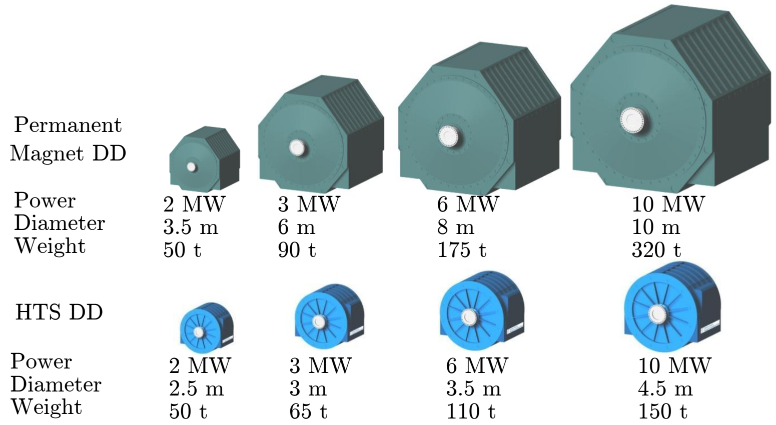

Figure 16: Size and mass comparison of direct-drive permanent magnet generator and superconducting generator for different power ratings [20].

presented in Figure 18. The data for each generator can be found in [21]. The dashed line represents ratio of generator mass to torque for permanent-magnet machines which is estimated as 25 kg/kNm by Bang et al. in [1]. The continuous line represents the linear trend line estimated using the HTS machines in the graph). It can be seen from the graph that HTS machines are generally lighter than PM generators for applications with torque requirements larger than 3000 kNm.

The most common superconducting machine type is a hybrid superconducting synchronous machine, which is a synchronous machine with a superconducting dc-field winding [22, 23]. This type of superconducting machines have high power density, but require cryogenic couplers and field excitation brushes in the rotor structure, which causes reliability problems.

There are some companies interested in superconducting wind turbines. Converteam -now acquired by General Electric- proposed an 8 MW, 12 rpm superconducting generator, which will be 5 m in diameter and weights approximately 100 tonnes [24]. American Superconductor (AMSC) aims to manufacture a 10 MW direct-drive superconducting generator: SeaTitan, which will have an outer diameter of 4.5-5 m and weights 150 tonnes [25].

GE Global Research (in partnership with Superconductor Technologies Inc.) aims to design a 10 MW direct-drive low- temperature superconducting generator -using MgB2 wires. The generator is planned to have a stationary superconducting field winding to reduce cryogenic-coupler faults. Another company is Advanced Magnet Lab., which plans to design a 10 MW, 10 rpm, 70 tonnes fully-superconducting generator. The ac losses on the armature coils can be minimized using their patented double-helix winding arrangement.

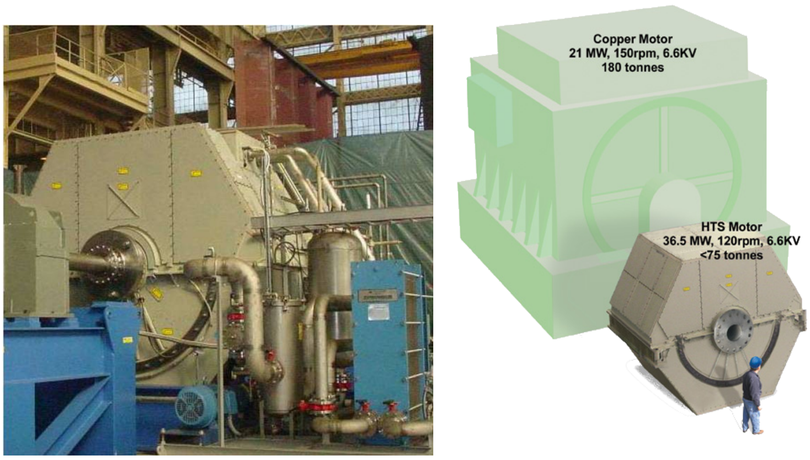

Figure 17: 36.5 MW superconducting ship propulsion motor for comparison with a conventional propulsion motor US Navy and size (Courtesy of AMSC).

SupraPower, an EU FP7 project has been initiated in 2012 [26], aims to build a reliable, lightweight synchronous generator, which was patented by Tecnalia [27]. The generator design has independent modular superconducting coils, which can be easily replaced, but the design still needs rotary feed-through.

The high efficiency of superconducting machines has been emphasized in the first applications, but efficiency is not solely sufficient. In order to penetrate into the renewable energy market, superconducting generators have to prove that they are also more reliable than alternative power take-off systems such as DDPM generators and geared DFIGs [28]. In a HTS machine, the cryogenic system holds the risk of decreasing the overall reliability. In particular, the cryogenic pump and couple are the most critical components. The cryogenic coupler can be eliminated by using a stationary superconducting field, which has many advantages [23, 29]:

- No cryogenic coupler, more robust and cheap cooling system
- No cryogenic coupler, more robust and cheap cooling system
- No brushes or complex excitation systems
- No centrifugal forces and transient torques that can damage the superconducting material

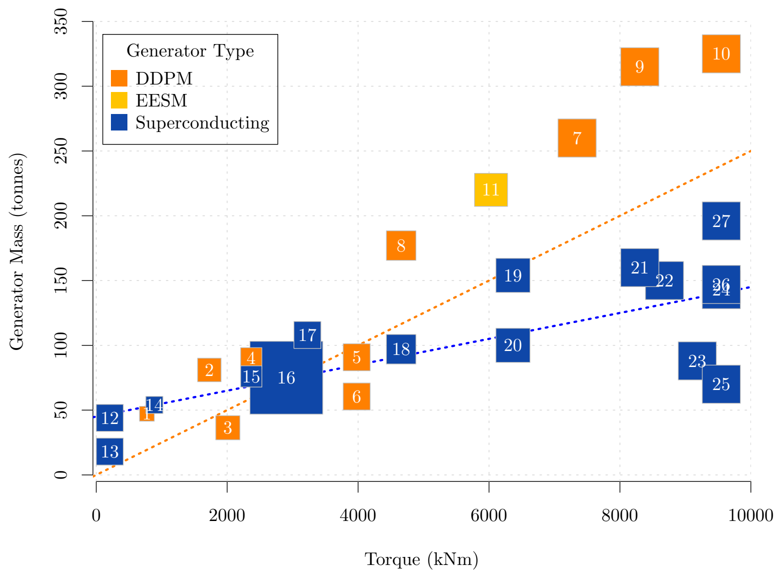

Figure 18: Mass of different large direct-drive machines as a function of the torque, area of the square represents the power rating. DDPM: Direct drive permanent magnet generator, EESM: Electrically excited synchronous machine, Superconducting: High-temperature superconducting generator. Orange line represents generator mass to torque ratio (m/T) of 25 kg/kNm for permanent-magnet machines as given in [1]. Blue line is the linear trend line for the superconducting machines.

References

1. D. Bang, H. Polinder, G. Shrestha, and Jan Abraham Ferreira. Review of Generator Systems for Direct-Drive Wind Turbines. In *Proceedings of the 2008 European wind energy conference, EWEC-2008*, pages 1–10, Brussels, 2008.
2. BVG. Offshore wind cost reduction pathways - Technology work stream. Technical Report May, BVG Associates, 2012.
3. Global Offshore Wind Energy Markets and Strategies: 2009–2020, Emerging Energy Research. Technical report, 2009.
4. UpWind- Design Limits and Solutions for Very Large Wind Turbines - EU 6th Frame Project. Technical report, 2011.
5. Wind Energy The Facts. http://www.wind-energy-the-facts.org/en/part-i-technology/chapter-3-wind-turbine-technology/technology-trends/drive-train-trends.html.

6. H. Li and Z. Chen. Overview of different wind generator systems and their comparisons. *IET Renewable Power Generation*, 2(2):123, 2008.
7. David Fickling. Rare Earth Elements -Beware of peak in rare-earth elements, 2011.
8. RL Moss, E Tzimas, H Kara, P Willis, and J Koorosh. Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. Technical report, JRC-IET Scientific and Technical Reports, 2011.
9. D. Bang. *Design of Transverse Flux Permanent Magnet Machines for Large Direct-Drive Wind Turbines*. Phd dissertation, Delft University of Technology, 2010.
10. D. Bang, H. Polinder, Ghanshyam Shrestha, and Jan Abraham Ferreira. Ring-shaped transverse flux PM generator for large direct-drive wind turbines. In *2009 International Conference on Power Electronics and Drive Systems (PEDS)*, pages 61–66. IEEE, November 2009.
11. H Li, Z Chen, and H. Polinder. Optimization of multibrid permanent-magnet wind generator systems. *Energy Conversion, IEEE . . .* , 24(1):82–92, March 2009.
12. G Bohmeke. Development and operational experience of the wind energy converter WWD-1. In *European Wind Energy Conference-EWEC*, 2003.
13. Artemis Intelligent Power. http://artemisip.com/our-technology, 2011.
14. Knud Erik Thomsen and Paul Chang. ChapDrive Hydraulic Transmission for Lightweight Multi-Megawatt Wind Turbines. In *International Conference on Drivetrain Concepts for Wind Turbines*, number October, Bremen, 2011.
15. B Diepeveen. Seawater-Based Hydraulics for Offshore Wind Turbines. Technical report, 2004.
16. Markus Mueller and A.S. McDonald. A lightweight low-speed permanent magnet electrical generator for direct-drive wind turbines. *Wind Energy*, 12(8):768–780, 2009.
17. A.S. McDonald, Markus Mueller, and H. Polinder. Structural mass in direct-drive permanent magnet electrical generators. *IET Renewable Power Generation*, 2(1):3, 2008.
18. JH van Wijk and M.J. Kamper. C-core topology for PM wind generators with non-overlap iron-cored stator windings. *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, pages MO441–MO441, 2010.

19. G. Klaus, W. Nick, H.W. Neumueller, G. Nerowski, and W. McCown. Development of High-Temperature Superconducting Electrical Machines at Siemens AG. In *International Conference on Electrical Machines, ICEM*, pages 1–6, 2006.

20. AMSC. Concepts for High Power Wind Turbines - Introducing HTS Technology. In *World Green Energy Forum*, 2010.

21. Ozan Keysan and Markus A. Mueller. A Homopolar HTSG Topology for Large Direct-Drive Wind Turbines. *IEEE Transactions on Applied Superconductivity*, 21(5):3523–3531, October 2011.

22. S.S. Kalsi, K. Weeber, H. Takesue, C. Lewis, H.W. Neumueller, and R.D. Blaugher. Development status of rotating machines employing superconducting field windings. *Proceedings of the IEEE*, 92(10):1688–1704, October 2004.

23. J. F. Gieras. *Advancements in Electric Machines (Power Systems)*. Springer, 2nd editio edition, 2009.

24. C. Lewis and Jens Muller. A Direct Drive Wind Turbine HTS Generator. *2007 IEEE Power Engineering Society General Meeting*, pages 1–8, June 2007.

25. G. Snitchler, Bruce Gamble, Christopher King, and Peter Winn. 10 MW Class Superconductor Wind Turbine Generators. *IEEE Transactions on Applied Superconductivity*, 21(3):1089–1092, June 2011.

26. Suprapower - Superconducting, reliable, lightweight and more powerful offshore wind turbine.

27. Gustavo Sarmiento Munoz, Jose Maria Merino Azcarraga, Javier Garcia-Tejedor Perez, Pedro Ibanez Ereno, and Susana Apinaniz. Direct-Action Superconducting Synchronous Generator for a Wind Turbine, 2011.

28. A. B. Abrahamsen, N. Mijatovic, E. Seiler, T Zirngibl, C Træ holt, P B Norgå rd, N. F. Pedersen, N. H. Andersen, and J Ostergå rd. Superconducting wind turbine generators. *Superconductor Science and Technology*, 23(3):034019, March 2010.

29. Ozan Keysan and Markus A Mueller. A Transverse Flux High-Temperature Superconducting Generator Topology for Large Direct Drive Wind Turbines. In *Superconductivity Centennial Conference*, volume 01, pages 1–6, 2011.