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Large superconducting wind turbine generators

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Abstract

To realize large (>10 MW) direct-driven off-shore wind turbines, a number of steps are needed to reduce weight and cost compared to on-shore technologies. One of the major challenges is to provide drive trains which can comply with the large torque as the turbine rotor diameter is scaled up and the rotation speed is lowered in order to limit the tip speed of the blades. The ability of superconducting materials to carry high current densities with very small losses might facilitate a new class of generators operating with an air gap flux density considerably higher than conventional generators and thereby having a smaller size and weight [1, 2]. A 5 MW superconducting wind turbine generator forms the basics for the feasibility considerations, particularly for the YBCO and MgB_2 superconductors entering the commercial market. Initial results indicate that a 5 MW generator with an active weight of 34 tons, diameter of 4.2 m and length of 1.2 m can be realized using superconductors carrying 300 A/mm^2 in a magnetic field of 4 T and an air gap flux density of the order 2.5 T. The results are compared to the performance of available superconductors, as well as the near future forecasted performance.

Superconductors; off-shore wind turbines; generators

1. Introduction

For off-shore harvesting of wind energy, turbines with power ratings of 10 MW and above are considered to bring down the installation costs per unit power, because the cost of the foundation is only scaling slowly with the power rating. The cost of energy determined by the turbine production over the 20 year lifetime is however the main performance indicator and will depend on the turbine reliability. Thus

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when up-scaling the present technologies to these power levels one will have to limit the increase in weight and thereby installation cost, while maintaining a sufficient reliability.

Historically, failures of gearboxes have been reducing the reliability of off-shore turbines, and there has been a trend in the industry towards omitting the gearbox by introducing direct drive technologies based on copper field windings or permanent magnets (PM). The copper based ring generator of Enercon tends to become big with a diameter of 12 m and heavy with a top head mass of around 500 tons for the 6 MW turbine E-112 [3]. The 6 MW PM direct drive turbine SWT-6.0 recently introduced by Siemens has a top head mass of about 360 tons and illustrates the potential of the PM technology [4]. However, the usage of the strong $R_2Fe_{14}B$ magnets based on rare earth elements R = Nd and Dy is of the order 600 kg/MW and will impose a considerable increase in the worldwide demand. China is producing 95% of the rare earth element and has recently imposed export quotas causing a tenfold increase in the Nd price. Thus the PM direct drive generator market will be quite sensitive to supply and price fluctuations.

The up-scaling of the off-shore turbine will depend on the development of longer blades, because the wind power at the turbine shaft scales with the swept rotor area A

$$P = ½\rho v^3 A C_P \qquad (1)$$

where ρ is the air density, v is the wind velocity, $A = \pi R^2$ is the swept rotor area and C_P is the power coefficient of the rotor blades depending on the ratio between the tip speed $V_{tip} = R\omega_S$ and the wind speed as well as the pitch angle of the rotor blades. Noise and load concerns are usually imposing an upper limit of the tip speed of turbine blades, and one will therefore have to reduce the rotation speed ω_S as the length R is increased. The torque on the turbine shaft T_S is related to the power of the turbine P by $T_S = P/\omega_S$, which is indicating a scaling $T_S \sim R^3 \sim P^{3/2}$. Thus the drive trains of the future up-scaled turbines are expected to handle very high torques approaching 10 MNm for a 10 MW turbine [5].

Superconducting generators hold the potential of providing high torques in a smaller size and with smaller weight than conventional technologies [1, 2], but there are two major challenges which must be addressed before a large scale utilization can be obtained. The first is the price of the superconducting wires. The second is to demonstrate the reliability of the technology seen from a system perspective including the cooling technology.

In this paper we give an introduction to superconductor technologies, discuss the superconductor generator, superconductor wire performances, and summarize the results of 5 MW superconductor generator design examples.

2. Superconductor basics

Superconductors are materials which carry electric currents almost loss-free, when cooled down below their critical temperature T_C. The current carrying capability, or the critical current density J_C, depends on the temperature and on the magnetic field, which the conductor is exposed to. Low-temperature superconductors typically operate at or below the temperature of liquid helium at 4.2 K. These conductors have found their market in MRI diagnostics system and in high-energy physics laboratories. The more recently discovered high-temperature superconductors (HTS) operate in the 20 - 80 K temperature range, depending primarily on the magnetic field and on the current density required. A steady development of these conductors has lead to gradually improved properties and lower costs. Still, there are only a few commercial applications utilizing the technology [6].

For wind turbine generators, the high current densities of the superconductors, over 100 times higher than in conventional copper conductors, open for new compact designs. The replacement of the copper conductors of the rotor, carrying DC currents, is the prime focus. Under AC conditions, as in the generator stator, the superconductors experience losses, which although small require costly cooling at low temperatures. The cooling of a DC rotor, on the other hand, is based on readily available cooling technologies and equipment reducing the heat loss and cooling power requirements to an acceptable level.

3. Superconducting generators

The most common suggestion of the topology of a superconducting direct drive wind turbine generator [1, 2] is illustrated in Fig. 1, showing a multi-pole rotor based on superconducting race track coils [5]. The coils are mounted on a support structure, which must be able to transfer the torque to the turbine shaft at room temperature. The rotor will typically contain steel laminates to concentrate the magnetic flux to the air gap and a cryostat to maintain a good thermal insulation of the superconducting coils. The main advantage of the superconducting rotor is that the flux Φ created by the superconducting coils will be proportional to the DC operation current I, $\Phi \sim LI$, where L is the self inductance of the coil, but the loss of the coil will not scale with the current I raised to an exponent of 2 as dictated by Ohm's law, $P = RI^2$, because the electric field E across a superconductor scales as a power law, $E = E_0(I/I_C)^n$, where $E_0 = 10^{-4}$V/m and the exponent n is between 10 and 40. One can therefore consider creating air gap magnetic flux densities higher than the saturation limit of the steel laminates of the rotor and thereby obtain a more compact generator. A consequence of the high magnetic flux density is also that the magnetic teeth of the stator should be avoided in order to lower the losses in the steel laminates. The stator of a superconducting generator is often suggested to be the air-cored type with non-magnetic support of the stator windings and steel laminate positioned outside to confine the magnetic flux.

3.1. Torque of synchronous superconducting generator

A superconducting generator is operated as a synchronous machine, because the magnetic field created by the stator is experienced as stationary by the superconducting field windings and the AC losses are therefore minimal. The torque of such a machine can be derived by assuming that the magnetic flux density in the air gap is harmonic, $B(\theta) = B_0\cos(p\theta)$, where B_0 is the peak flux density and p is the pole number. By additionally assuming a harmonic current distribution of the stator in the coordinate system of the rotor, $I_S = A_S \cos(p(\theta + \gamma))$, where γ is the angular displacement of the current distribution relative to the rotor field distribution, then one can determine the torque T by integrating the force F acting on each stator wire at radius R, $dT \sim R \times F$, where the Lorentz force on each wire is $F \sim I_S \times B$

$$T \propto B_0 A_S R^2 l \cos(p\gamma) \qquad (2)$$

A_S is the rms armature loading in units of [A/m], R and l are the air gap radius and length of the machine [7].

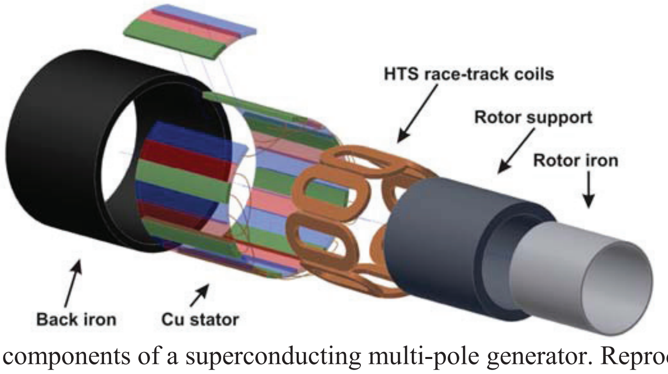


Fig. 1. The main components of a superconducting multi-pole generator. Reproduced from [5].

3.2. Advantages of a superconducting generator

In the introduction it was argued that the future drive trains of large off-shore turbines must handle large torques either in the gearbox or in a direct drive generator. Equation (2) can be used to illustrate the difference between a conventional and a superconducting machine. The peak flux density B_0 of a conventional machine is limited by the saturation of the steel laminates, being around 1.5 T and can not be exceeded without extensive Joule heating dissipated in the field windings. The electric loading of the armature winding is also limited by the Joule heating and the available cooling, being either air or liquid based. Thus if the limits of the two above quantities are reached in a generator design, then the only option of obtaining a higher torque is to increase the volume of the generator.

The decoupling between the flux generation and of the joule heating of superconducting field coils does however allow for an increase of the peak flux density of the air gap, and it is seen from equation (2) that the torque increases proportionally with B_0. Thus if B_0 is increased from typically 1 T in a conventional machine to 2 T in a superconducting machine, then there is a potential of twice the torque in the same volume. Many of the challenges of such generators are connected to obtaining feasible designs incorporating the cooling technology. Here the choice of superconductor will have a large influence on the possible operation temperature, which will be discussed in the next sections.

4. Superconductor wire performance

A large development effort is needed before a new superconducting material can be turned into a practical conductor for large scale applications, because the superconducting material must be incorporated in a composite conductor structure with additional metal supporting the superconducting phase. This has most successfully been obtained by the powder-in-tube (PIT) method, where a superconducting powder enclosed in a metal tube is extruded to a long wire. Often several wires are combined into a twisted multifilament wire, which is finally enclosed in a metal sheath. The PIT method has been applied to the NbTi (T_C ~10 K), Nb_3Sn (T_C~ 18 K), MgB_2 (T_C ~ 39 K) and the high temperature superconductor $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (T_C ~ 110 K). The high temperature superconductor $YBa_2Cu_3O_{6+x}$ (T_C ~ 93 K) has intrinsic critical current properties superior to Bi-2223, but unfortunately conductors can not be produced by the PIT method, because the Cu-O planes in different ceramic grains must be aligned within a few degrees in order to support a supercurrent. An alternative conductor geometry has therefore been developed, where YBCO grains are deposited onto an aligned metal substrate. We will review the properties of the YBCO coated conductors and the MgB_2 PIT tapes below.

4.1. YBCO superconductors

Fig. 2a shows the architecture of the coated conductor consisting of an oriented metal substrate and several ceramic buffer layers, which are deposited in order to prevent diffusion of metal elements into the final YBCO layer, which will inherit the alignment from the metal substrate [8]. The advantage of the YBCO superconductor is that the critical current density is of the order of $J_C \sim 3 \cdot 10^4$ A/mm^2 at $T = 77$ K and in zero applied field. The typical YBCO layer is only 1 μm thick, resulting in a critical current of the order $I_C = J_C \cdot 4$ mm$\cdot 10^{-3}$ mm = 120 A. The engineering critical current density J_e is defined as I_C divided by the entire cross section area of the tape A_{tape} giving J_e = 120 A / 4 mm·0.1 mm = 300 A/mm^2, since the thickness of a coated conductor tape is 0.1 mm. A racetrack coil based on coated conductor from American Superconductor is shown in Fig. 2b and contains a stainless steel former onto which the coated conductor tape has been wound with glass fiber tape inserted as electrical insulation. Cu blocks are used for current support [7]. Such a coil is a small scale example of the superconducting field coils shown in Fig. 1. The price of coated conductor is high due to the vacuum techniques involved in the manufacturing process and is generally quoted as 30 €/m. One can evaluate the price over performance by also dividing with the critical current I_C of the tape, which gives 247 €/kA·m at $T = 77$ K and in zero field.

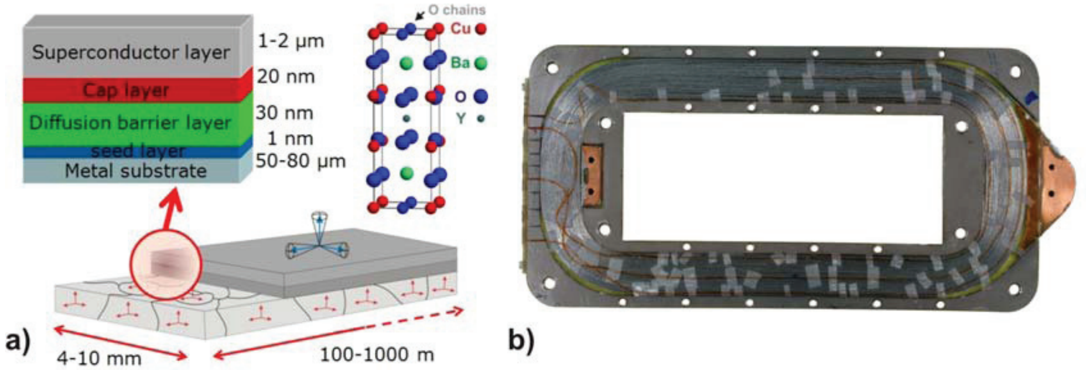
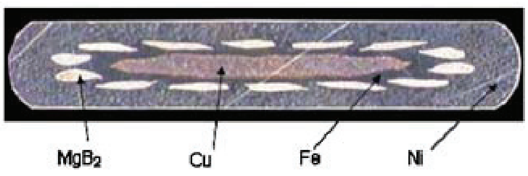


Fig. 2. a) Architecture of coated conductor based on bi-axially aligned $YBa_2Cu_3O_{6+x}$ high temperature superconductor deposited on textured buffer layers and a metal substrate. Inset: Crystal structure of YBCO. Reproduced from [8]. b) Example of racetrack coil wound from 30 m or 70 m of coated conductor tape from American Superconductor and Superpower, respectively. Reproduced from [7].

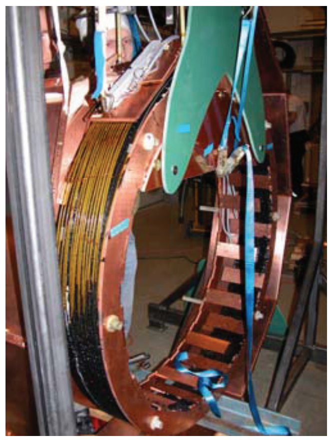
4.2. MgB_2 superconductors

The conductor is produced by the PIT method, and Fig. 3a shows the cross-section of a tape-formed 14 filament MgB_2 wire with a nickel matrix, a copper core for thermal stabilization and an iron layer obstructing reactions between the MgB_2 compound and the copper during production [9].

The MgB_2 conductor has found its first applications in the medium magnetic field range (1 - 2 T) for MRI systems, with the reduced conductor and/or cooling costs as the main driver. Presently, the wire price is in the order of 1 - 3 €/m and with 7 €/kAm for MRI (20 K, 1 T) [9]. Also other applications are considered. In Fig. 3b a 10 H MgB_2 coil made from MgB_2 wires for an induction heater application is shown [10].



(a)



(b)

Fig. 3. a) Cross-section of a MgB_2 superconductor with 14 MgB_2 filaments (Courtesy Columbus Superconductors). b) A 10 H, 1.1 m in diameter coil wound from 8 km of MgB_2 superconductors.

4.3. Magnetic field and temperature scaling of engineering critical current

Fig. 4 is showing how the critical current of a coated conductor and a MgB_2 wire is decreasing as function of the applied magnetic field and as the operation temperature is approaching the critical temperature T_C. The scaling of the coated conductor I_C is obtained from magnetization measurements, which are normalized by the response obtained at T = 77 K [7]. Transport data of the I_C scaling of a standard tape is shown by the symbols and indicate a discrepancy which is believed to be connected to a lower I_C = 100 A. The MgB_2 scaling is derived from transport critical current measurements in [11] on an un-doped monocore strand by normalizing with the cross section area of wire. The scaling data is needed in order to determine the working point of superconducting coils by ensuring that the current in the coils remains below the critical current, which is decreased due to the field produced by the coil.

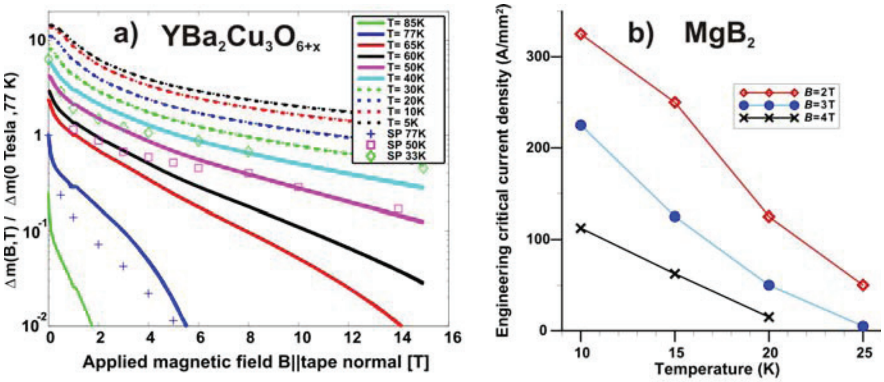


Fig. 4. a) Scaling factor of the critical current of a coated conductor as function of the applied field and temperature of a Superpower tape with I_C = 125 A at T = 77 K and in zero field [7]. b) Engineering current density of an un-doped monocore strand manufactured by Hypertech Research [11].

5. A 5 MW superconducting wind turbine generator

A feasibility study of a 5 MW direct drive superconducting generator, which could replace the gearbox based drive train of a Repower 5M turbine has recently been performed in order to clarify the working conditions of the superconductors. Fig. 5a shows the magnetic field distribution of a 24 pole generator with an active diameter of D = 4.2 m, length of L = 1.2 m and an air gap peak flux density of 2.5 T obtained by having J_e = 300 A/mm^2 in the superconducting field winding [7]. This J_e could be obtained if current coated conductors from Superpower could be utilized to their full potential. From Fig. 5a it is seen that this superconductor will be exposed to a maximum field of 4 T, and from the scaling in Fig. 4a one can obtain an estimate of the operation temperature by looking for a scaling factor of *1* at 4 T. This indicated an operation temperature between 30 and 40 K, which can be obtained using cryocooler technology. The active mass of the components shown in Fig. 5a is estimated to 34 tons, and the usage of coated conductor amounts to L_{SC} ~ 130 km. The current price of the superconductors will be 3.9 M€, which is too high compared to the expected price for off-shore wind power of 1.5 M€/MW, giving 7.5 M€ per 5 MW off-shore turbine including foundation and cable to land.

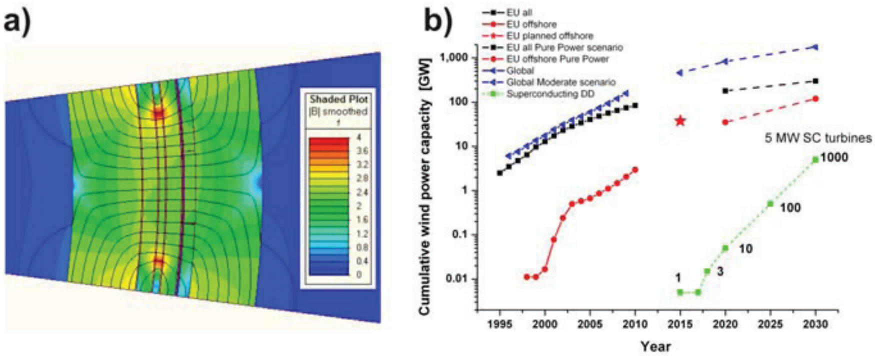


Fig. 5. a) Magnetic flux density of a 24 pole generator. From left: rotor steel, cryostat, superconducting windings and support, cryostat, air gap, armature windings and stator steel. b) Roadmap of introduction of superconducting wind turbines in the European off-shore market. Reproduced from [7, 8].

6. Discussion

The 5 MW generator examples illustrate that the superconducting technology does provide a technically interesting solution, but that the current price is too high compared to the total price of the off-shore installation if based on the coated conductor. The advantage of the superconducting drive train is however expected to become more evident as the turbine rating is up-scaled towards 10 - 15 MW, and secondly, the price of the coated conductors is also expected to decrease, because the wind application could generate a large demand. This can been seen by considering a road map for the introduction of the superconducting wind turbines compared to the Europe and worldwide wind capacity as illustrated in Fig. 5b [8]. The current worldwide production of coated conductors is of the order of 2000 km/year and shows that the first 5 MW SC turbine could be installed by 2015 for reliability testing before another three turbines are installed in 2018, ending with about 10 turbines in 2020. This would form a solid learning basis for up-scaling the production by two orders of magnitude with 5 GW capacity by 2030 to make any significant impact on the wind market. A tape production of around 13000 km/year from 2020 to 2030 would be needed, but this number would come down if the properties of the tape are improved, because less tape must be used, also resulting in a more compact design.

It is also interesting to investigate whether the inexpensive MgB_2 wire is an alternative to the expensive coated conductor. From Fig. 4b it is seen that the presently available conductors, an operating temperature below 10 K is required for a 2.5 T generator design to become viable with J_e = 300 A/mm^2 and 4 T at the conductor. However, there is an ongoing development of the MgB_2 wires, which may be of particular importance in the 3 - 4 T range. For instance, Columbus Superconductor has predicted an increase in their wire performance from 130 A/mm^2 at 10 K, 4T in 2010 to 500 A/mm^2 at 10 K, 4T in 2013 [9]. Such a development would open up for the possibility to use MgB_2 conductors in wind power generators also in the 10 - 20 K temperature range. To illustrate the impact we will use a 16 pole 2.5 T generator design similar to that of Fig. 5a, but based on a superconductor with J_e = 70 A/mm^2 [7]. A mass of 3 tons of coated conductor tape, equivalent to 332 km was estimated, and if this length is replaced directly with MgB_2 at a price of 1 €/m, one will have a superconductor price being approximately 330 k€, which is an order of magnitude cheaper than the present coated conductor solution. Thus the MgB_2 wire is interesting for wind turbine generators, but it remains to be proved that the lower operation temperature can be handled by the cryostat and the torque transfer tube without causing a poor cooling efficiency and thereby high operating costs.

7. Conclusions

A 5 MW generator example shows that the coated conductor machine will have superior properties compared to MgB_2, but a high cost of 3.9 M€ with current tape prices. MgB_2 wires have presently not a sufficient current density of J_e = 300 A/mm^2 in 4 T field to replace the coated conductor, but if a lower J_e = 70 A/mm^2 in assumed, it might become possible to utilize MgB_2 with an estimated price of 330 k€ for the superconductors of a 5 MW generator. Finally, a road map of introducing superconducting turbines is indicating the production volume of both coated conductor and MgB_2 wire must be in the order of 10000 km/year from 2020 to 2030 to make an impact on the wind power market.

Acknowledgements

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