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Potential of MgB_2 superconductors in direct drive generators for wind turbines

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Abstract

Topologies of superconducting direct drive wind turbine generators are based on a combination of superconducting wires wound into field coils, copper armature windings, steel laminates to shape the magnetic flux density and finally structural materials as support. But what is the most optimal topology for superconducting wind turbine generators?

This question is investigated by assuming some unit cost of the different materials and then minimizing the cost of the active materials of a 10 MW and 9.65 rpm direct drive wind turbine generator intended to be mounted in front of the INNWIND.EU King-Pin concept nacelle. A series of topologies are investigate by adding more iron components to the generator, such as rotor back iron, field winding pole, magnetic teeth and armature back iron. This method is used to investigate 6 topologies and to determine the optimal cost of the different topologies by using the current cost of 4 €/m for the MgB_2 wire from Columbus Superconductors and also a possible future cost of 1 €/m if a superconducting offshore wind power capacity of 10 GW has been introduced by 2030 as suggested in a roadmap. The obtained topologies are compared to what is expected from a permanent magnet direct drive generators and the further development directions are discussed.

Finally an experimental INNWIND.EU demonstration showing that the current commercial MgB_2 wires can be wound into functional field coils for wind turbine generators is discussed.

Keywords

Superconducting generator, direct drive, wind turbine, cost optimization, MgB_2, INNWIND.EU, MgB_2 coil demonstration

1. Introduction

Superconducting electrical machines have been investigated since the successful manufacturing of the NbTi wire, which is made of many filaments of the superconducting NbTi metal alloy enclosed in a copper matrix. The NbTi wire has developed gradually since the 1960s and a series of machines were investigated until the 1980s [1], but a serious barrier for commercialization was the need for liquid helium for cooling the machines to 4 K (-269 °C) and the challenging thermal insulation. Today NbTi is used heavily in about 20000 Magnetic Resonance Imaging (MRI) Scanners in hospitals around the world [2]. The critical temperature, T_c, is 9.8 K, the critical current density, J_c, is approximately 2000 A/mm^2 at 4.2 K & 10 T and finally the unit cost is about 0.4 €/m [3].

In 1986 a new class of ceramic superconductors was discovered and since these superconductors become superconducting at a much higher temperature they are called high-temperature superconductors (HTSs). They can be cooled with liquid nitrogen, boiling at 77 K (-196 °C) and this relatively high temperature was believed to facilitate commercialization of superconducting machines for power generation and ship propulsion[4]. The higher operation temperature also allowed for the use of closed-cycle helium based cooling machines, which only need electricity and not a supply of a cryogenic liquid such as liquid helium or liquid nitrogen. The processing of the HTS wires is however expensive and the unit cost is in the order of 30 €/m [3] with current densities of 200 A/mm^2 at 20-30 K and 1-3 T [5].

In 2001 it was discovered that the simple metal alloy MgB_2 became superconducting at a temperature of 39 K (-234 °C). This temperature is high enough to still use the close-cycle cooling machines and MgB_2 therefore holds the potential to be a cheaper alternative than the high temperature superconductors for many superconducting applications[3]. MgB_2 provides a compromise between a reasonable super-conducting current density J_e ~ 100-200 A/mm^2 in 1-2 Tesla and an operation temperature in the range 15-25 K [3]. MgB_2 wires have been developed and are offered by only two manufacturers today: Columbus Superconductors SpA [6] and Hyper Tech Research Inc [7]. The unit cost of the MgB_2 is shown in table 1.

2 Superconducting wind turbine generators

The application as a compact high torque and slow speed generator for direct drive wind turbines was identified as a shift from ship propulsion and into the wind sector by American Superconductors (AMSC). The 10 MW SeaTitan turbine from AMSC is based on their high temperature superconducting tape [8]. Several other companies and research institutions have also proposed wind turbine generators based on the HTS[9,10] as well as both NbTi[11,12] and MgB_2 wires[13].

There are basically two philosophies behind the design of superconducting generators:

1) The high current density of the superconducting wire is used to make field coils with no iron cores that produced a magnetic flux density, which is exceeding the saturation flux density of the usual magnetic steel.

2) The high current density of the superconductor is used to magnetize conventional magnetic steel providing as closed a magnetic flux path as possible of the generator.

A consequence of option 1) is that more superconducting wire is needed to provide the amp-turns for producing the needed magnetic flux of the machine and secondly the magnetic flux density at the superconducting winding will be several teslas, which is suppressing the critical current density of the superconductor. The thermal insulation of the superconducting coil might be more simple. This philosophy is well suited for the cheap NbTi wire and has been applied by GE in a 10 MW design [11], which basically transfers the MRI technology to the wind turbine generator. AMSC has also applied philosophy 1) for the SeaTitan generator [8].

The second option is quite close to the normal way of building generators, because the only function of the superconducting winding is to provide very compact amp-turns in a relatively low magnetic field. However, the use of magnetic steel in the center of the superconducting field coils increases the cold mass and result in longer cool-down times as well as larger forces acting inside the thermal insulation. One may however consider to position the magnetic steel outside the cryostat at room temperature. This will provide an almost closed magnetic flux path and the challenge is then to construct the thermal insulation of the superconducting coils.

This second option was originally proposed by Technalia for a 10 MW MgB_2 turbine and is investigated in the FP7 project SUPRApower [13], in their case with a slotless armature winding. This salient-pole concept with HTS has been investigated more extensively for wind turbine applications [9].

In this paper it is investigated how the cost of the active materials can be reduced by increasing the amount of iron in a series of superconducting machine topologies. This will provide useful input for the final design of the cryogenic cooling system, because the thermal insulation will be very different for the two philosophies outlines above.

2.1 MgB_2 model generator

In order to investigate the impact of the amount of iron in the machine a general generator pole model was described in the finite element code

COMSOL as shown in figure 1. First the main topology T4-T9 is chosen by specifying the materials which the different parts of the generator are made of according to table 1. The topology T4 consists of an air-cored superconducting field winding supported by non-conducting glass fiber material, G10. The armature winding is also of the air-cored type in order to reduce the magnetic flux ripple, which is causing AC losses in the superconductor. Only the Armature winding back material is chosen to be magnetic steel to confine the magnetic flux inside the machine. The subsequent topologies T5-T9 are obtain by choosing the field back, the field pole piece and the armature teeth to also be made of magnetic steel [14].

Figure 2 shows the critical current density of a number of MgB_2 tapes from Columbus superconductors, which is used for a INNWIND.EU coil demonstration [15]. The question is at what magnetic flux density and temperature it is best utilized. The magnetic steel used for the generator is standard steel for electrical machines.

2.2 Generator topology optimization

The topology optimization routine is checking if the operational current density *J* of the superconducting windings are at least 25 % lower than the critical current shown in figure 2 using 2D FE calculations taking into account the non-linear saturation of the steel laminates for a given generator configuration. Then the length of the generator is determined to match the torque requirement of the turbine and the cost of the active materials is determined from the active masses and the assumed unit costs from table 1. If the cost of a topology configuration is lower than the previous then this is used for further optimization [14].

Material	Unit cost [€/kg]
MgB_2 wire (MgB2) 3.0 mm x 0.7 mm (m = 16.7 kg / km)	4 €/m → 1 €/m 240 → 60
Copper (Cu)	15
Steel laminates (Fe)	3
Glass-fiber (G10)	15
Permanent Magnet(PM)	50-75

Table 1: Unit cost of active material of MgB_2 superconducting generator [14].

Figure 3 shows a series of magnetic flux density maps of the topologies (T4 to T9) with an increasing amount of iron in the generators as well as the cost of the active material after the minimization. It is seen that more iron in the flux path of the magnetic circuit reduces the amount of superconductor needed. Thus the total cost is decreasing from about 1800 k€ for T4 to 800 k€ for the iron based topology T9. By using the permanent magnet unit cost in table 1 then the cost of the PM materials is expected to be in the order of 350 k€- 525 k€ by assuming a usage of 7 tons PM for a 10 MW turbine [16]. This is the same order of magnitude as the iron based MgB_2 machines indicating that the two technologies will be quite similar from an active material cost perspective.

2.3 Supply chain investigation

The MgB_2 wire is however not a mature technology and it is relevant to ask what is expected to happen with the wire cost in the future in case it will be used more. Figure 4 shows a suggestion to a scenario of how to introduce 10 GW of superconducting offshore capacity compared to the current capacity and future predictions [17]. The basic idea is to introduce the first 10 MW turbine around 2020, but then to scale up the production of superconducting turbines considerable in order to have approximately 10 GW by 2030. From figure 3 it can be determined that 200-60 km of MgB_2 wire is needed for a 10 MW machine for the topologies T4-T9 with a wire unit cost of 4 €/m. This will result in a wire demand of about 60000 – 200000 km up until 2030. The current production volume of Columbus superconductors is about 3000 km per year [6], whereby the lower limit can be met with only a limited investment. The cost of the wire is however also expected to decrease if the scenario of figure 4 is realized and a lower level of 1 €/m could be considered. Using such a unit cost and running the optimization for the T4-T9 topologies result in the second set of active material costs marked with * in figure 3. The active material cost will then decrease from about 1000 k€ to 600 k€ going from T4-T9 and the MgB_2 usage will be 340-100 km. In figure 4 the MgB_2 wire usage is shown in terms of tons of wire and is compared to the usage of PM for a permanent magnet direct drive.

3. Discussion

It might seems like the MgB_2 generator would become cheaper than the PM, but it should be remembered that the cost of the cryogenic cooling system have still not been included. A first attempt to include the cryogenic costs have been done for a warm iron cored field winding similar to the T9 topology and it was shown that the amount of MgB_2 wires needed could be reduced from 100 km in the analysis above to about 20 km for the entire 10 MW generator [18]. An evaluation of the Levelized Cost of Energy (LCoE) of the INNWIND.EU 10 MW reference turbine holding such a MgB_2 generator indicated a relative decrease in the order of ΔLCoE ~ - 0.4 % ± 2 % as compared to a medium speed drive train [19]. The uncertainty in the LCoE is estimated by the uncertainties in the cryogenic cooling and generator structural support design.The INNWIND.EU reference turbine used for the analysis has a power rating of 10 MW provided by a 178 m diameter rotor elevated to a hub height of 119 m [20]. The turbine is designed for the wind class Ia with an average wind speed of 10 m/s representing an offshore environment with a water depth of 50 m. The turbine is installed on a jacket foundation [21] and the reference drive train is of the medium speed type scaled from 4 MW to 10 MW [22]. The evaluation of the LCoE of different INNWIND.EU turbines are done by combining the cost estimates for the blades, the drive train, the tower and the foundation adding an estimate for the operation and maintenance (OPEX) and then deviding the total cost by the Annual Energy Production (AEP) of the different concepts taking the partial load efficiency into account [23, 24].

It is found that the SCDD 10 MW generator [25] can reach a full load efficiency of 96.5 % [19], which is reduced to about 94.9 % when including the losses of the power electronics [26]. This is basically the same effeciency as the medium speed drive train in [22]. The SCDD is expected to have a constant loss of about 50 kW used to run the cryocoolers even when the wind speed is below the cut-in wind speed of 4 m/s. Using the class Ia wind distribution one can estimate that this condition is found in 1550 hours per year and correspond to a loss of 77.5 MWh per year, which is 0.2 % of AEP. Thus this loss will have an impact similar to the estimated LCoE, but is believed to be included the uncertainty estimate of the LCoE. The cost of the SCDD is estimated to be similar to the medium speed drive train as analysed in 2012 using prices of permanent magnets ranging from 60 – 150 €/kg [22]. It is however shown by Schmidt and Vath in [22] that the medium speed drive train only shows a small sensitivity to the PM price due to the presence of the gearbox. Thus the cost comparison is believed to be resonable.

The above analysis indicates that the superconducting MgB_2 wind turbine generators have the potential to become as cheap as the PM direct drive, but further analysis and experimental demonstration is needed to clarify if any issues with reliability and availability of the superconducting wind generator will make the PMDD superior.

Before a 10 MW MgB_2 generator can be realized the coil winding technology must be established at an industrial scale. Figure 5 shows the design of a MgB_2 race track coil in the INNWIND.EU project [15]. A challenge with the MgB_2 wire is that the tension along the wire must not exceed 110 MPa, because interfaces between the MgB_2 grains will break and the critical current will be permanently reduced. Work is ongoing to calculate the thermal stress building up in the coil as it is cooled to 15-20 K and the additional stress from the Lorentz force. The winding of the double pan-cake coils is ongoing and the testing of the magnet is expected in the spring of 2016 to provide high field experimental data on the wire properties as they are integrated into a large race track coil.

4. Conclusion

The cost analysis shows that the cheapest MgB_2 direct drive generator will have as much iron as possible in the magnetic circuit and is pointing to the salient pole generator concept introduced by the SUPRApower project [13]. The cost analysis also indicate that the MgB_2 direct drive generator will have a hard time to compete with the permanent magnet direct drive in terms of active material cost if the philosophy is to use a lot of iron in the generator and to only expect lower MgB_2 cost in the future. An additional improvement of the critical current density of the wires must probably also have to be considered as suggested by Hypertech proposing a 5-fold increase of the critical current density in some years [27].

A roadmap of introducing 10 GW of superconducting offshore turbines is used to argue that the volumes of MgB_2 wire needed is not too far from what Columbus Superconductors can produce in EU, but the small number of possible suppliers of MgB_2 wires will probably be considered a risk in the supply chain. On the other hand the MgB_2 technology is lifting the potential dependence on Rare Earth Elements(REE), which has previously been considered a major supply chain risk for the production of $R_2Fe_{14}B$ permanent magnets. From figure 5 it can be seen that 10 GW of PMDD will correspond to about 7000 tons of PM material over a period of 10 years.

Finally demonstrations of coil winding techniques are needed to mature the MgB_2 technology for the wind sector and the INNWIND.EU MgB_2 racetrack coil demonstration is expected to provide experimental data on the wires in coils and for verification of finite element models of coils for further generator design.

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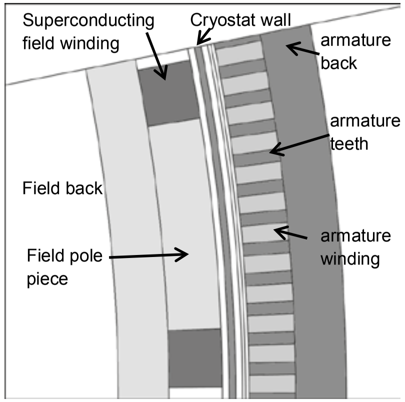

Figure 1. Model layout of a generator pole with the following components from left to right: field winding back, superconducting coil, field pole piece, air gab, cryostat wall, armature windings, armature teeth and armature back.

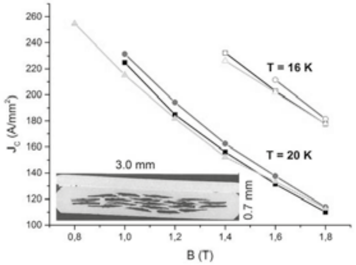

Figure 2. Critical current density of 3 different MgB_2 superconductor wires as function of operational magnetic flux density at different temperatures. **Inset:** Cross section image of the tape. MgB_2 filaments (black) are enclosed in anickel matrix and a copper strip is soldered on top.

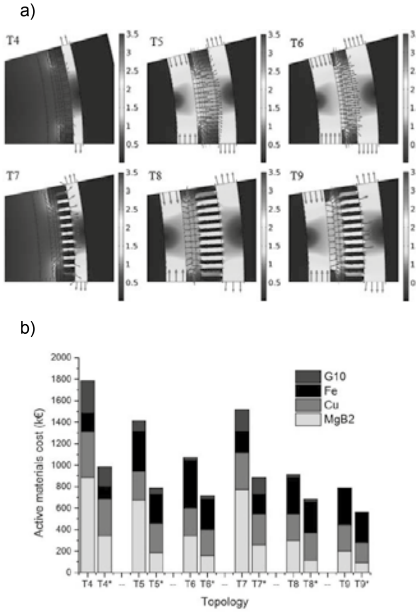

Figure 3. **a)** Topologies of 10 MW direct drive wind turbine generator with an increasing amount of iron components included in the design of the rotor and armature configuration (T4: iron behind armature, T5: add rotor back iron, T6: add field coil iron pole, T7: iron teeth for support of armature, T8: add rotor back iron and T9: add field coil iron pole) [14]. Topologies T1-3 have no back iron of the armature and has been omitted due to high cost. **b)** Active material cost of topologies after minimizing the cost for a D = 6.0 m generator intended as front mounted on the INNWIND.EU king-pin nacelle configuration [25]. The solutions indicated with a star is assuming that the price of the MgB_2 wire is reduced to 1 €/m from the current level of 4 €/m [14].

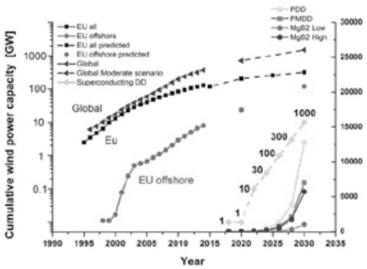

Figure 4. Scenario for market introduction of 10 GW superconducting wind turbines (green) in comparison with the past and expected future development of installed wind power capacity for all of EU (black) and offshore (red). The needed supply of permanent magnet (PM) material and MgB_2 wire are plotted with reference to the right hand axis by assuming a usage of 700 kg PM /MW for the direct drive and 10-35 km MgB_2 / MW for the superconducting MgB_2 direct drive generators.

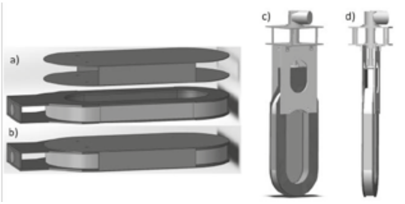

Figure 5. Illustration of INNWIND.EU superconducting race track coil demonstration based on a stack of 10 double pan-cake coils of MgB_2 superconducting wire with a 3.0 mm x 0.7 mm cross section. **a)** A stainless steel cover is fitted around the MgB_2 race track coil (gray) and enclosed between copper plates (brown) to provide the cooling at the circular end-plate (blue). The straight section of the coil is 0.5 m and the inner opening is 0.3 m. **b)** Assembled race track coil with the thermal and mechanical support. **c)** Mounting of the MgB_2 race track coil by hanging it inside a cryostat with the outer wall holding the top plate at room temperature. A cryocooler cold head is inserted into the cryostat wall and cools down a radiation shield (lower plate) to about 70 K. The coil is hanging in two glass fiber plates (yellow) and is supported by two rods going through the coil and a glass fiber support inside the coil. **d)** The second stage of the cryocooler coldhead is cooling the thermal support of the coil (blue circle of b) to the operation temperature of 10-20 K.