Potential of MgB_2 superconductors on direct drive generators for wind turbines

Asger B. Abrahamsen[1], Dong Liu[2], Niklas Magnusson[3] and Henk Polinder[2].

[1]DTU Wind Energy, Technical University of Denmark, Denmark.

[2]Electrical Power Processing Group, Delft University of Technology, The Netherlands

[3]SINTEF Energy Research, Norway.

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1. Introduction (75 words: 84)

We have investigated how to cost optimize 10 MW superconducting direct drive generator topologies with an increasing amount of iron parts in the active materials and for MgB_2 superconducting wires. A wire cost from 4 €/m and down to 1 €/m assuming learning indicates that a salient pole generator is cheapest, but the cost is quite similar to the permanent magnet direct drive. It seems that wire improvement scenarios must be considered and a coil demonstration is proposed to mature the coil winding technique.

2. Approach (300 words: 288)

Topologies of superconducting direct drive generators are based on a combination of superconducting wires wound into field coils, copper armature windings, steel laminates to shape the 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 generator intended to be mounted in front of the INNWIND.EU King-Pin concept nacelle [1]. A series of topologies are investigate by adding more iron components to the generators, such as rotor back iron, field winding pole, magnetic teeth and armature back iron. This method is used to investigate 6 topologies shown in figure 1 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 [2] 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 the roadmap of figure 2. The obtained topologies are compared to what is expected from a permanent magnet direct drive and the further development directions are discussed.

Finally experimental demonstrations that the current commercial MgB_2 wires can be wound into functional field coils for wind turbine generators are needed. The INNWIND.EU project [3] is working on such a demonstration experiment (see figure 3) to de-risk the coil winding procedure and to confirm the finite element calculations used for the cost optimization. The coil demonstration is focused on the fabrication of 10 double pan-cake coils, which can be stacked into a composite race track coil.

3. Main body of abstract (600 words: 788)

The superconductor MgB_2 is providing a compromise between a reasonable superconducting current density J_e ~ 100-200 A/mm^2 in 1-3 Tesla and an operation temperature in the range T = 15-25 K, which can be obtained with advanced cooling machines called cryocoolers [4]. The questions of how to utilize theses wires in a direct drive wind turbine generator is however central and especially the task to relate it to the expected cost of the generator system. Here it is done by assuming some unit cost of the active materials used in the generator as shown in table 1. The topology optimization routine is checking if the superconducting windings are within the J_e safety margin of 25 % 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. If the cost of a topology configuration is lower than the previous then this is used for further optimization [5].

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

Table 1. Unit cost of active material of superconducting generator.

Figure 1 is showing 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 is reducing the amount of superconductor needed. Thus the total cost is decreasing from about 1800 k€ for T4 and 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 [6]. 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.

The MgB_2 wire is however not a very mature technology and it is relevant to ask what is expected to happen with the wire in the future in case it will be used more. Figure 2 is showing a suggestion to a scenario of how to introduce 10 GW of superconducting offshore capacity compared to the current capacity and future predictions. 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 1 it can be determined that between 200-60 km of MgB_2 wire for a 10 MW machine is needed for the T4-T9 with a 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 [2], whereby the lower limit can almost be meet. The cost of the wire is however also expected to decrease if the scenario of figure 2 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 materials cost marked with * in figure 1. 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 2 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. It might seem that 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.

Finally before a 10 MW MgB_2 generator can be realized then the coil winding technology must be established on an industrial scale. Figure 3 is showing the design of a MgB_2 race track coil in the INNWIND.EU project [7]. 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 T = 15 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 end of 2015 to provide high field experimental data on the wire properties as they are integrated into a large race track coil.

4. Conclusion (300 words: 253)

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[8]. The cost analysis also seems to 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 [9].

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 MgB2 technology is lifting the potential dependence on Rare earth elements, which has previously been considered a major supply chain risk.

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.

5. Learning objectives (25 words: 19)

Superconducting direct drive wind turbine generators, Cost optimization using the MgB_2 superconductor wire and INNWIND.EU MgB_2 coil demonstration experiment.

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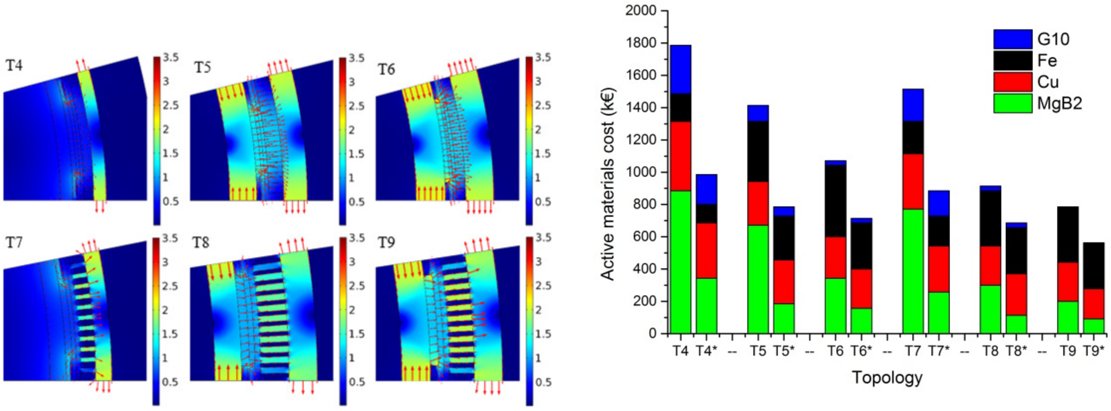

Figure 1. **a)** Topologies of 10 MW direct drive wind turbine generator with an increasing amount of iron components included in the design of the rotor and armature configuration (T4: iron behind armature, T5: add rotor back iron, T6: add field coil iron pole, T7: iron teeth and support of armature, T8: add rotor back iron and T9: add field coil iron pole) [Dong paper]. **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 [EWEA 2014 paper]. The solutions indicated with a star is assuming that the price of the MgB_2 wire is reduced to 1 €/m compared to the current level of 4 €/m [Dong Paper].

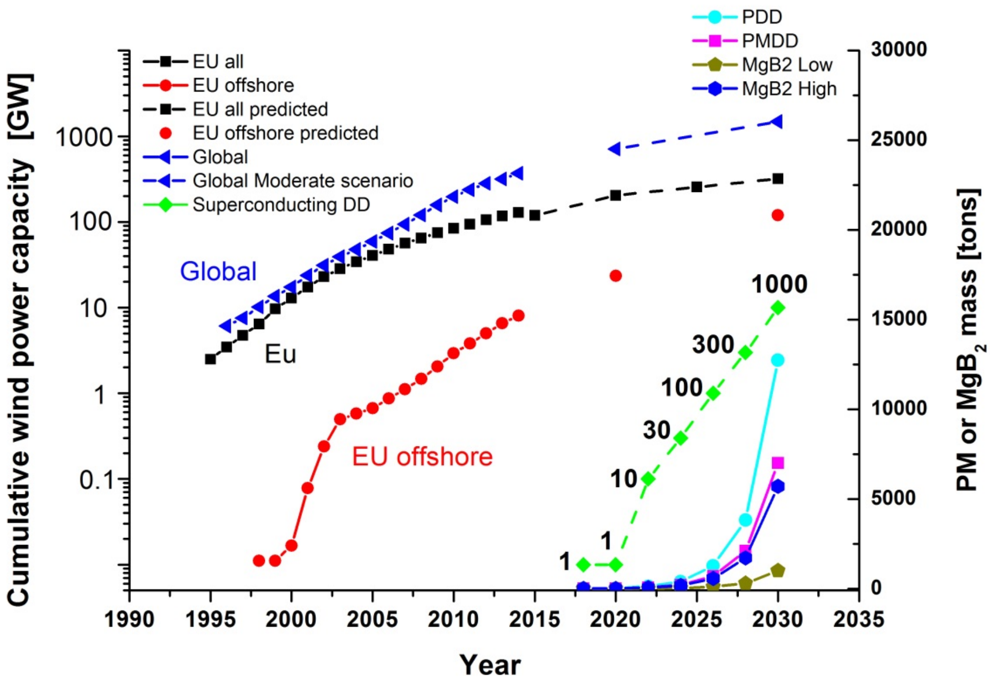

Figure 2. Scenario for market introduction of 10 GW superconducting wind turbines (green) in comparison with the past and expected future development of installed wind power capacity for all of EU (black) and offshore (red). The needed supply of permanent magnet (PM) material and MgB_2 wire are plotted 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.

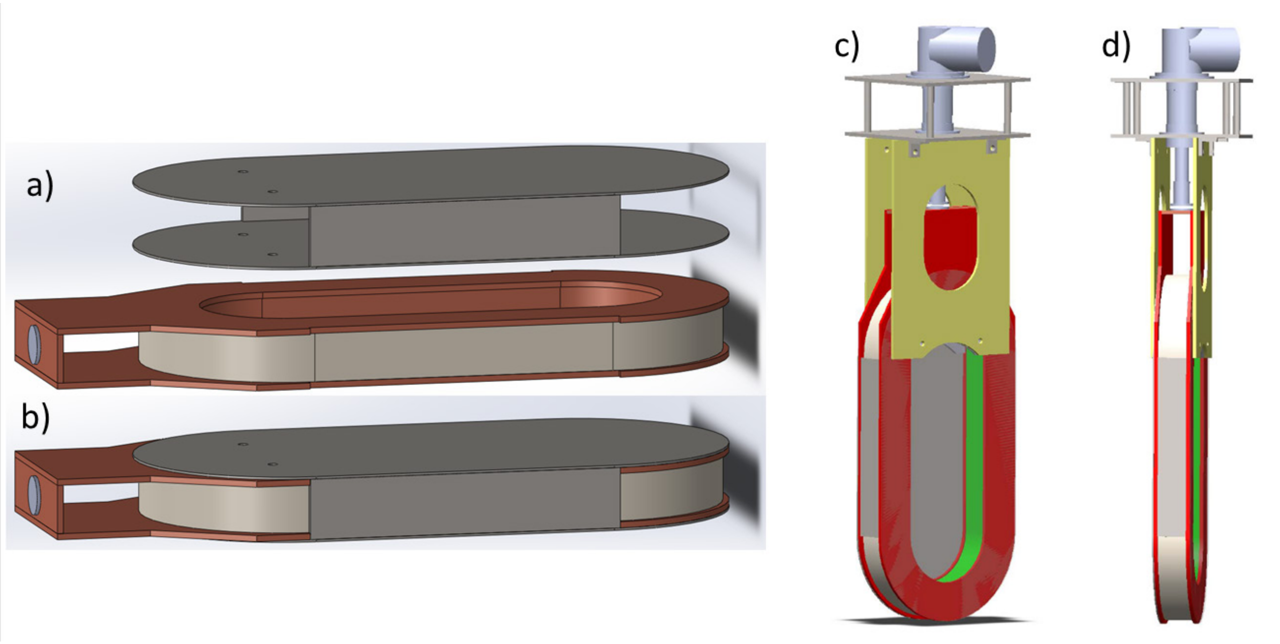

Figure 3. Illustration of INNWIND.EU superconducting race track coil demonstration based on a stack of 10 double pan-cake coils of MgB_2 superconducting wire with a 3.0 mm x 0.7 mm cross section. **a)** A stainless steel cover is fitted around the MgB_2 race track coil (gray) and enclosed between copper 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 large 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 40 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 10-15 K.