Design study of a 10 MW MgB_2 superconductor direct drive wind turbine generator

Asger B. Abrahamsen
DTU Wind Energy
asab@dtu.dk

Niklas Magnusson
SINTEF Energy Research
Niklas.Magnusson@sintef.no

Dong Liu
Delft University of Technology
D.Liu-1@tudelft.nl

Ewoud Stehouwer
DNV-GL
ewoud.stehouwer@dnvgl.com

Ben Hendriks
DNV-GL
ben.hendriks@dnvgl.com

Henk Polinder
Delft University of Technology
H.Polinder@tudelft.nl

Abstract

A superconducting direct drive generator based on field windings of MgB_2 superconducting tape is proposed as a solution by mounting the generator in front of the blades using a king-pin nacelle design for offshore turbines with power ratings larger than 10 MW as investigated in the INNWIND.EU project.

Keywords: superconducting generator, direct drive generator, offshore wind turbine, nacelle integration.

1 Introduction

Offshore wind power demands larger turbines than what is used onshore in order to decrease the cost of energy. This is due to the fact that the income of any horizontal axis turbine is scaling with the area of the rotor ~ R^2, whereas the mass is often expected to scale with approximately ~ R^3, because the blades need to be longer, wider and thicker. Furthermore, for offshore turbines the foundation must be added and the mass of this will only scale with ~ R^2, because the water depth h is fixed. Since the foundation is more expensive than the turbine, a minimum of the cost of energy is expected for a larger turbine. The offshore turbine will however still be challenged by the square-cubic scaling of the mass and innovations of all turbine components as well as the foundations improving this scaling are investigated in the INNWIND.EU project for power ranges, P, of 10-20 MW [1].
The technology-mix of drive trains of large offshore turbines tends to diverse into gearbox combinations with either fast- or medium speed generators and to direct drive generators, where the omitted gearbox is believed to increase the reliability [2]. Direct drive generators have been introduced as both the wound field and permanent magnet type, but the scaling of these types of machines might become a challenge above 10 MW. The shear stress F_d of a radial multi-pole generator is given by the product of the peak value of the fundamental air gap magnetic flux density B_g and the peak value of the fundamental current loading A_S of the armature windings

$$F_d = \frac{1}{2} B_g A_S cos\gamma \qquad (1)$$

where γ is the angular displacement between the rotor and armature field and current distributions [2]. Equation (1) illustrates that the air gap flux density B_g and the current loading A_S dictate how large a generator has to be in order to provide a sufficient torque in a turbine, because the torque is the shear stress multiplied by the air gap surface area. It is interesting to note that the air gap flux density is limited to about 1 T in most radial flux generators, because of saturation of the magnetic steel and the limits of the permanent magnets. Similarly the current loading of the armature is limited by resistive heating, which must be removed by active cooling.
These limits can however be circumvented by introducing superconducting materials in such generators, because the superconductors have vanishing small resistivity at high current densities and also at high magnetic flux densities. This can be utilized in wires, which can transport current densities in the order of 100 –1000 A/mm^2 without the joule heating, which often limits the current density in copper to below 5 A/mm^2. The major drawback is however that the superconducting state is only obtained at very low temperatures, in the range -269°C to -163°C (4-110 K) and therefore cryogenic cooling technology is needed to maintain such low temperatures. The main superconducting candidates for electrical machines are NbTi embedded in copper wires, MgB_2 embedded in nickel/copper wires and the high-temperature superconductors RE-$Ba_2Cu_3O_{6+x}$ (REBCO) deposited on metal strips (where RE are any of the Rare Earth elements) [3]. Superconductors can be used to create DC

air gap flux densities of several Tesla by making coils of superconducting wires carrying a constant current in a synchronous generator. For the armature windings the situation is a bit different since AC magnetic fields and AC currents generate losses in the superconductor. Although there are several proposals of superconducting armature windings [4] & [5], such a solution depends on a substantial superconducting wire development to reduce these AC losses to an acceptable level [6].
From the present cost of the different superconducting wires, the MgB_2 superconductor seems attractive with a relatively high operation temperature of 15-20 K and sufficiently low wire cost [3].
This paper provides a design study of a 10 MW direct drive wind turbine generator based on MgB_2 wires, which are used to produce an air gap flux density of the order of 1.5 T exceeding values for conventional machines. The cost of the active materials of the generator is estimated and discussed in terms of the INNWIND.EU target values for the cost of capacity [M€/MW]. Secondly a nacelle structure is presented for further investigation of the integration of such a superconducting generator into offshore turbines with power ratings larger than 10 MW. The paper is organized by first introducing a down scaled MgB_2 rotor coil intended for demonstration, then it discusses the 10 MW generator obtained by extending the length of the demonstration coil and finally a front mounted generator nacelle design is presented.

2 Rotor coil design

An experimental demonstration of a down-scaled MgB_2 coil suitable as the field winding of a direct drive wind turbine is planned for in the INNWIND.EU project [1]. The demonstrator coil has a shorter length, but the same width as a 10 MW generator coil (with a sufficient number of poles on a cylindrical support), generating the same maximum field as in the 10 MW generator.

2.1 MgB_2 conductor

The demo coil is based on a conductor in the form of a tape, which is 3 mm wide and 0.5 mm thick. Filaments of the superconducting MgB_2 material are embedded in a nickel matrix, which is formed by extrusion of a composite billet and rolled flat into the final dimensions. A copper strip of 3 mm width and 0.2 mm thickness is soldered onto the tape to provide electrical protection of the tape in case the superconducting state is lost due to some extreme conditions in the application. The tapes can be bent into a diameter of $D_{critical}$ = 15 cm without breaking the superconducting filaments and that sets a limit to how small the opening of the rotor coil can be. Kapton tape is applied to the tape to provide electrical insulation. The tape is produced by Columbus Superconductors. The present cost of such tapes are 4 €/m, but the cost is predicted to decrease to about 1 €/m as the production is scaled up in a few years [6] & [7].

2.2 Coil layout

The demonstration coil is composed of 10 double pancake coils, which are stacked into a race track coil with a straight section of 0.5 m and an end winding diameter of 0.3 m being two times larger than the critical bending diameter $D_{critical}$ of the tape. The cross section of the coil is 84 mm x 80 mm including Kapton insulation and epoxy used for wet-winding of the tapes [6]. Figure 1 shows the shape of the race track coils and the arrangement of the tapes within the windings.

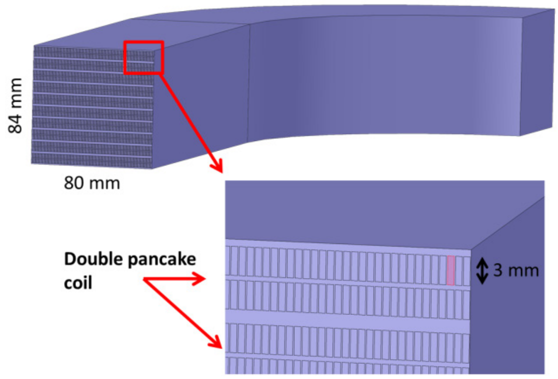

Figure 1: Illustration of one quarter the superconducting MgB_2 demonstration racetrack coil geometry with a straight section and a circular end-section. The race track coil consists of 10 double pancake coils stacked on top of each other. The inset shows an enlarged view on the MgB_2 tape windings of the pancake coils. The cross section 3 mm x 0.7 mm of an MgB_2 tape (including the copper strip) is indicated as the red box.

The MgB_2 tape becomes superconducting at 39 K and the coil is designed to support an engineering current density of $J_{E,coil}$ = 70 A/mm^2, which is defined as the current I in the wire divided by the cross section area A_{cross} of the wire, insulation and epoxy.

$$J_{E,coil} = \frac{I}{A_{cross}} \qquad (2)$$

This current density must be sufficiently lower than the critical engineering current density $J_{E,C}$ of the superconducting wire, which is obtained by inserting the critical current I_C in equation (2). The critical current I_C is often defined as the current at which the voltage drop per unit length E (electric field) is 10^{-4} V/m. The electric field, E, observed along the superconducting wire is given by a power-law dependency (in contrast to normal metals which follow Ohm's law).

$$E = E_0 \left(\frac{I}{I_C(B,T)}\right)^{n(B,T)} \qquad (3)$$

where $E_0 = 10^{-4}$ V/m . The n-value indicates that the voltage will change highly non-linear, since n is typically in the order of 10-20, whereas n = 1 represents Ohm's law. The voltage criterion given by E_0 is arbitrary and is just defining the power dissipation $P_0 = E_0 \cdot I_C$ in the wire at I_C. Thus if I_C = 100 A then $P_0 = 10^{-4}$ V/m·100 A = 10^{-2} W/m, which must be removed by the cooling system having a poor efficiency in the order of 1 % at cryogenic temperatures [3]. Thus P_0 will be equivalent to 1 W/m if the cryogenic penalty is taken into account. This dissipation can be greatly reduced by operating the superconductor at say 75% of its critical current, since $(I/I_C)^n = 0.75^{20} = 3.2 \cdot 10^{-3}$.
The critical current $I_C(B,T)$ depends on both the operation temperature T and the magnetic field B applied to the wire, due to the physical properties of the superconductor. The scaling is roughly $I_C \sim 1/B$ and will decrease as the critical temperature T_C of the superconductor is approached. Thus a central aspect in the design of a superconducting generator is to determine the current operation point of the field coils by taking into account the local field and temperature distribution.

3 Generator design

A conventional design based on a synchronous multi-pole machine with superconducting field coils and an air-core armature of copper at ambient temperature is chosen for this study. The superconducting field coils are supported by a non-magnetic structure and inserted in a cryostat providing thermal insulation. The armature is enclosed by steel laminates to confine the magnetic flux in the generator. Figure 2 shows a section of the generator pole geometry. The torque, τ, requirement of the generator is dictated by the 10 MW INNWIND reference turbine, 10.6 MNm at a rotation speed, ω, of 9.7 rpm.

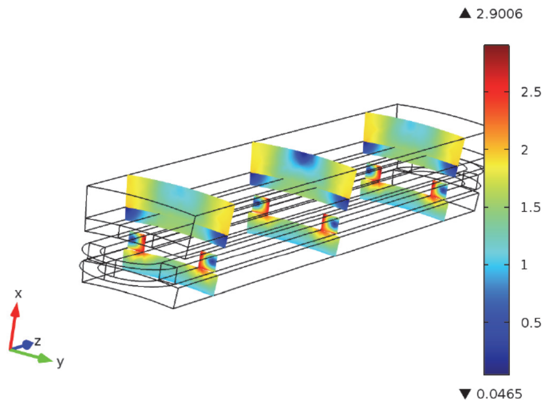

Figure 2: Geometry of a pole with a non-magnetic support at the bottom followed by the superconducting race-track field coil, the air-cored armature windings and the steel lamination confining the flux in the generator. The color plots show the magnetic flux density in selected cross sections of the pole.

The approximate size of a direct drive generator is determined from equation (1) by assuming a target air gap flux density of ~ 1.5 T and a current loading of the armature of 100 kA/m resulting in a shear stress of F_d = 75 kNm/m^2. Analytical expressions for the magnetic flux density in an air-core superconducting generator as described by Kalsi [7] were used to determine the number of poles and also to determine how much the straight section of the demonstration coils have to be expanded to comply with the torque requirements. Table 1 shows the resulting dimensions and properties of a 32 pole generator with an outer diameter of 5.8 m and an active length of 3.1 m.
Finite element modeling was used to determine the magnetic flux density imposed on the inner part of the field coils in both the straight and the end-sections of a pole by imposing periodic boundary conditions for the 32 poles. From figure 2 it is seen that the magnetic flux density reaches 2.8 T at the inner windings of the straight sections of the racetrack coil and an examination of the end sections reveals a magnetic flux density of 2.9 T. The load line of the generator field coils is constructed by plotting the maximum magnetic flux density of the straight and end-sections as the current loading J_E of the field coils are increased. This is illustrated in figure 3 where the load line is overlaid with the critical engineering current density $J_{E,C}$ of the MgB_2 tape as function of the applied magnetic flux densities at different temperatures [6]. From figure 3 it is seen that the operation temperature will have to be in between 10 and 15 K in order to have a margin to the critical current density of about 25%. Thus the

cryostat and the support of the superconducting MgB_2 field coils must be designed to meet this requirement. Secondly this temperature range can be reached by cryocooler machines and will therefore allow operation without the need of liquid helium as in the magneto-resonant imaging MRI scanner at many hospitals.
Before discussing the cryostat design further, the integration into the turbine nacelle is addressed.

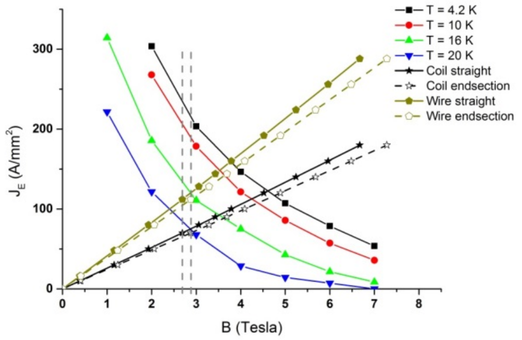

Figure 3: Load line of the 10 MW MgB_2 generator race track coils (fig. 2.) relating the magnetic flux generated at the inner turns of both the straight and the end-sections to the engineering current loading J_E of the coils. This load line must be sufficiently below the critical engineering current density $J_{E,C}$ of the MgB_2 superconducting wire and operation in a field around 3 Tesla indicates and operation temperature between 10-15 K. Reproduced from [6].

4 Nacelle integration

The target power range of the INNWIND.EU project is 10–20 MW and the loads on a 20 MW nacelle of a horizontal axis turbine with a blade diameter reaching 250 m will be very large. Thus it was investigated if a nacelle design could be found that would be applicable to the entire power range. Figure 4 shows the integration of the 10 MW MgB_2 generator into a nacelle, which has the potential to be up-scaled towards 20 MW. The nacelle is based on a king-pin, holding two main bearings mounted on each side of the hub. This results in relatively low main bearing loads and allows for rotors with large diameters. A direct drive generator can be mounted in front of the turbine blades by attaching the rotating outer ring of the generator to the hub. This layout eases the installation and the maintenance. The generator could also be mounted behind the rotor blades, but the front mounted superconducting generator is considered as the most promising, because the empty space inside the generator gives more freedom for the design of the cryogenic cooling system.
A central question is whether to mount the superconducting field coils to the rotating frame or in the stationary frame of the nacelle. Figure 4 shows a solution where the MgB_2 field coils are fixed to the stationary king-pin, while the armature is rotating. Thus, this has the consequence that the full power must be transferred to the nacelle using slip rings. This idea was recently introduced by GE Global Research for a direct drive superconducting generator based on the low temperature superconductor NbTi [8]. The authors of [8] argued that the slip rings used in hydro power plants constitute a well proven technology and that the advantages of a simpler cryogenic system balance the lower reliability of the slip rings.
The alternative of mounting the superconducting field coils on the outer rotating frame will remove the need of the slip-rings to bring the full power to the nacelle, but then brings the challenge of transferring either:

a) Power to drive machines, if the cryomachines are mounted in the rotating frame.
b) High pressure helium gas from compressors in the nacelle frame to cold-heads mounted in the rotating frame.
c) Cold cryogenic gases or fluids produced in the nacelle frame to the rotating frame holding the cryostat.

The option a) is considered hard because most cryogenic cooling devices will not operate properly if turned upside-down. The option b) has been proposed by American Superconductors for their 10 MW SeaTitan turbine based on coated conductor high-temperature superconductors [9]. Option c) has been investigated by GE power conversion [10], but the reliability of the system is not publicly available. The solutions outlined above as well as the design of a cryostat supporting the superconducting field coils will be investigated in future work of the INNWIND.EU project.
But before such detailed designs are carried out more work must be done to optimize the generator integration into the nacelle as discussed below.

5 Discussion

From table 1 it can be seen that the total amount of MgB_2 tape needed for the proposed generator is of the order of 474 km. Secondly, it is seen that the single piece length of MgB_2 tape needed is of the order of 741 m, which complies very well with the available piece-lengths of 1-2 km. Thus the tape is about ready to be used for the application, but the analysis of the cost remains. Using the present cost of the tape of 4 €/m and adding the cost of the active materials one obtains a cost per capacity of 226 €/kW (see table 1). This should be compared to the 20% share of the offshore turbine price 1500 €/kW covered by the gearbox and generator giving a threshold of 300 €/kW. Taken into account that the cost of the MgB_2 tape is expected to decrease to 1 €/m with an up-scaling of production to comply with a demand imposed by the wind sector, then it seems plausible that the threshold can also be fulfilled when including the cost of the structural mass and the cooling system.

The diameter of the presented generator has been limited in order to match the size of the nacelle hub, but it has been investigated how the amount of active material will change if the outer diameter of the generator is increased. This has been done by adding more poles and only changing the active length of the MgB_2 field coils, but keeping the coil opening and cross section constant [14]. Figure 5 illustrates how the active masses scaled to the initial total active mass of the R = 2.7 m design will decrease as the diameter is increased. It is seen that the amount of MgB_2 needed for the generator can be reduced by almost a factor of two for a D = 12 m generator and with an active length of L_{active} = 0.5 m. This is roughly the dimension of the proposed INNWIND.EU MgB_2 demonstration coils mentioned in the introduction and it will therefore show if the coil concept is feasible for the machines represented in figure 5. Since the MgB_2 wire cost is the major contribution to the cost of the active material a considerable cost saving can be done by increasing the diameter of the machine. The structural support of the active materials as well as the cryostat including a torque tube for transferring the torque from the hub to the cold coil support must however also be taken into account. This will be investigated further in the INNWIND.EU project for evaluation of the cost of energy for the entire offshore turbine.

6 Conclusions

A 10 MW direct drive superconducting wind turbine generator based on MgB_2 superconducting wire has been analyzed in terms of properties, amount of wire needed and expected cost of the active materials. The diameter is 5.8 m and the active length is 3.1 m. A king-pin nacelle concept with the superconducting generator mounted in front of the rotor blades has been proposed, because it is believed to be one of the only ways to support a rotor approaching 250 m for a 20 MW turbine. Finally a cost of capacity analysis of the generator shows that the contribution from the active materials is 226 €/kW, which is lower than the INNWIND threshold of 300 €/kW. Cost reductions imposed by a decreasing wire price and an increase of the generator diameter indicate that the expenses of the cryogenic cooling systems can be accommodated. This will be further investigated in the INNWIND project and compared with conventional drive trains.

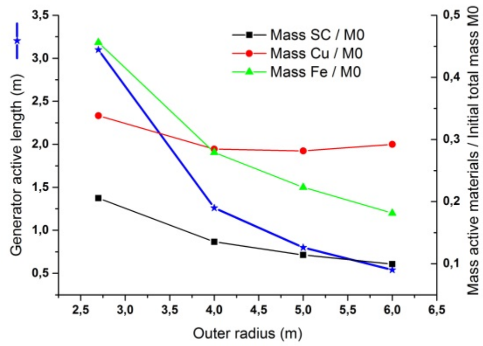

Figure 5: Trend analysis of the mass of the active materials (SC: superconductor, Cu: Copper and Fe: Laminates) of MgB_2 superconducting generators with increasing outer diameter and decreasing active length. The masses are scaled to the total initial mass M0 of the R = 2.7 m machine.

7 Acknowledgement

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$R_{Fe\ out}$ [m]	2.94	Torque [MNm]	10.6
$R_{Armature\ out}$ [m]	2.79	Speed [rpm]	9.65
$R_{Armature\ in}$ [m]	2.73	Poles [2p]	32
$R_{Supercond\ out}$ [m]	2.69	Frequency [Hz]	2.57
$R_{Supercond\ in}$ [m]	2.59	$B_{air\ gap}$ [T]	1.5
$L_{generator}$ [m]	3.1	Arm. loading [A/m]	10^5
R_{End} [m]	0.15	Arm. Fill [%]	50
W_{coil} [mm]	84	Shear stress [kN/m^2]	75
H_{coil} [mm]	80	Efficiency [%][1]	97.7
$L_{SC\ single\ pancake}$ [m]	740.9	J_{coil} [A/mm^2]	70 @ 3 Tesla
$L_{SC\ double\ pancake}$ [m]	1481.7	J_{tape} [A/mm^2]	113 @ 3 Tesla
$L_{SC\ Race\ track\ coil}$ [km]	14.82	M_{Cu} [kg]	19415
$L_{SC\ total}$ [km]	474.2	M_{Fe} [kg]	24998
Tape unit cost [€/m]	4 ($\rightarrow$ 1)	M_{active} [kg]	52331
SC cost [k€]	1897 ($\rightarrow$ 474)	Cost Cu [€]	291234
$M_{Superconductor}$ [kg]	7918.1	Cost Fe [€]	74994
$M_{cryostat+cooler}$ [kg]	TBD	Cost total [k€]	2263 ($\rightarrow$ 840)
Cost cryostat	TBD	Cost / cap. [€/kW]	226 ($\rightarrow$ 84)

Table 1: Properties of 10 MW 32 pole direct drive superconducting generator based on MgB_2 tape. Reproduced from [6]. [1]Cryogenic and power electronic losses are not included.

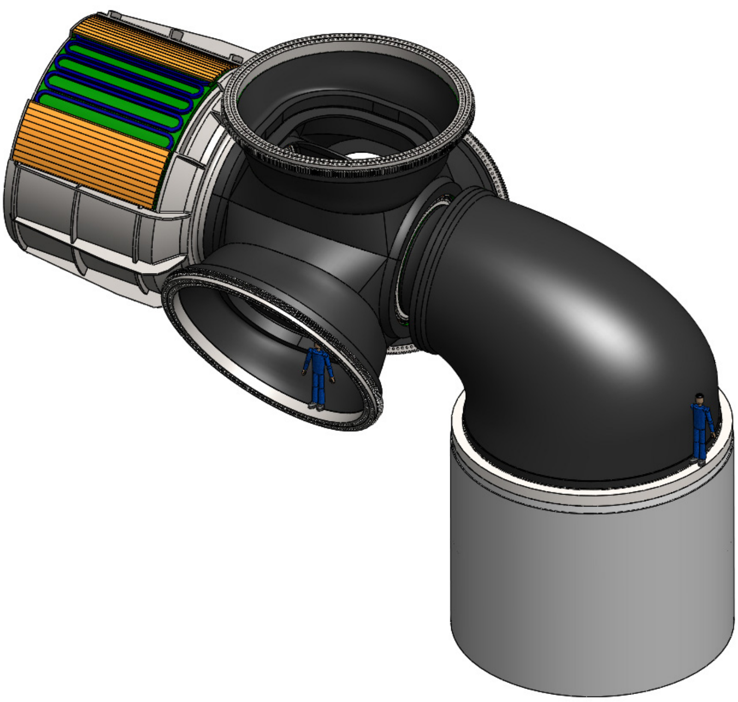

Figure 4: Integration of MgB_2 superconducting direct drive generator into a king-pin nacelle by mounting the generator in-front of the turbine rotor blades. It should be noted that the superconducting generator shown will have the superconducting field windings fixed to the stationary king-pin, whereas the armature is mounted to the rotating hub. This will simplify the cryogenic cooling system considerable, but the drawback is that the full power of the rotating armature must be transferred to the nacelle frame by large slip rings. The opposite configuration of outer rotating superconducting field coils and an armature fixed to the nacelle is currently being investigated in the INNWIND.EU project.