Design of an MgB_2 race track coil for a wind generator pole demonstration

2014 J. Phys.: Conf. Ser. 507 032001

(http://iopscience.iop.org/1742-6596/507/3/032001)

Design of an MgB_2 race track coil for a wind generator pole demonstration

Asger B. Abrahamsen[1], Niklas Magnusson[2], Bogi B. Jensen[3], Dong Liu[4] and Henk Polinder[4]

[1]Department of Wind Energy, Technical University of Denmark, Denmark
[2]SINTEF Energy Research, Norway
[3]Department of Electrical Engineering, Technical University of Denmark, Denmark
[4]Electrical Power Processing Group, Delft University of Technology, Netherlands

Corresponding author's e-mail[1]: asab@dtu.dk

Abstract. An MgB_2 race track coil intended for demonstrating a down scaled pole of a 10 MW direct drive wind turbine generator has been designed. The coil consists of 10 double pancake coils stacked into a race track coil with a cross section of 84 mm x 80 mm. The length of the straight section is 0.5 m and the diameter of the end sections is 0.3 m. Expanded to a straight section of 3.1 m it will produce about 1.5 T magnetic flux density in the air gap of the 10 MW 32 pole generator and about 3.0 T at the edge of the superconducting coil with an operation current density of the coil of 70 A/mm^2.

1. Introduction

Offshore wind power demands large turbines to drive down the cost of energy. In this respect, superconducting direct drive generators may be advantageous due to a better size scaling compared to permanent magnet technology for ratings above 10 MW [1]. Several superconductors are considered for use in the generator rotor, e.g. high-temperature superconducting (HTS) YBCO tapes (coated conductors) [2] and low-temperature superconducting (LTS) NbTi [3]. With a critical temperature of 39 K, the superconductor MgB_2 can be operated in the10-20 K range, well above the usual operation temperature of 4.2 K given by the boiling point of liquid helium for the LTS, and below the operation window of 25-27 K for cooling with liquid neon for the HTS. MgB_2 tapes and wires are produced by the Powder-In-Tube (PIT) method, which is simpler and cheaper than the thin film technology used for the coated conductors. Furthermore, the up-scaling to single piece lengths in the order of km is easier than for the coated conductors. This makes MgB_2 wires and tapes candidates for the field coils of wind turbine generators, although the large scale and in-field performance of the MgB_2 technology still needs verification.

2. Demonstration coil design

We have used MgB_2 engineering current densities of a tape from Columbus Superconductors in the order of 100-200 A/mm^2 in a magnetic field of 2-3 T, corresponding to operation temperatures of 10-20 K [4], to design a race track coil with a straight section of 0.5 m and bending diameter in the end section of about 0.3 m. The coil is targeted at a demonstration in a Ø 1.2 m cryostat equipped with a cryocooler providing a base temperature of about 10 K [5]. Conduction cooling is employed to extract

Journal of Physics: Conference Series **507** (2014) 032001 doi:10.1088/1742-6596/507/3/032001

Table 1. Layout of the MgB_2 race track coil.

Length strait section: L_{strait} [m]	0.5	Opening inside pancake: W_{coil}[m]	0.3
Radius of end winding: R_{end}[m]	0.15	Turns in pancake layer: N	100
Thickness of tape: $t_{SC,\ tape}$ [mm]	0.7	Width of tape: $W_{SC,\ tape}$ [mm]	3.0
Insulation thickness: t_{insul} [mm]	$2{\cdot}0.07 = 0.14$	Space between pancakes: W_{insul} [mm]	1
Coil winding thickness: t_{coil}[mm] [a]	84	Double pancake height: H_{DPcoil}[mm] [b]	7
Tape in pancake: $L_{singlepancake}$[m] [c]	220.8	Tape in double pancake: L_{DP} [m]	441.6
Pancake spacing: $L_{coilspace}$ [mm]	1	No. of double pancakes: $N_{pancakes}$	10
Field coil height: H_{coil} [mm] [d]	80	Total tape usage: $L_{tapetotal}$ [m]	4416
Field coil width: W_{coil} [mm]	84	Coil filling factor: f_{coil} [%] [e]	62.5

[a] $t_{coil} = N\cdot (t_{SC,tape} + t_{insul}) = N\cdot t_{wire}$
[b] $H_{DPcoil} = 2\cdot W_{SC,tape} + W_{insul}$
[c] $L_{singlepancake} = N\cdot[2\cdot L_{strait} + 2\pi R_{end}] + 2\pi\cdot t_{wire}\cdot N(N+1)/2$
[d] $H_{coil} = N_{pancakes}\cdot[H_{DPcoil} + L_{coilspace}]$
[e] $f_{coil} = A_{SC}/A_{coil}$

the heat from the coil. Table 1 lists a coil layout based on a series of stacked double pan-cake coils insulated with Kapton tape and impregnated with Stycast 2850. The amount of tape needed for the demonstration is about 4.5 km.

3. Direct drive 10 MW generator

A study of a corresponding 10 MW direct drive wind turbine generator has been conducted by keeping the cross section dimension of the coil constant, but to expand the length and increase the number of poles in the generator to comply with the specifications of the 10 MW INNWIND.EU reference turbine [6]. Figure 1 shows the magnetic flux density distribution in the cross section of the pole at a coil current density, J_{coil}, of 70 A/mm^2. (Note that J_{coil} is the current density of the wire times the coil fill factor). The generator consists of a non-magnetic support of the race track coils, a cryostat wall, an air-cored copper stator at ambient temperature and back-iron to contain the flux. The magnetic flux density at the coil will reach about 2.9 T in the straight section and about 3.0 T at the end section as shown in figure 2. The corresponding load line of both the straight and the end section of the coil are shown in figure 3 along with engineering current densities of the tape at different temperatures.

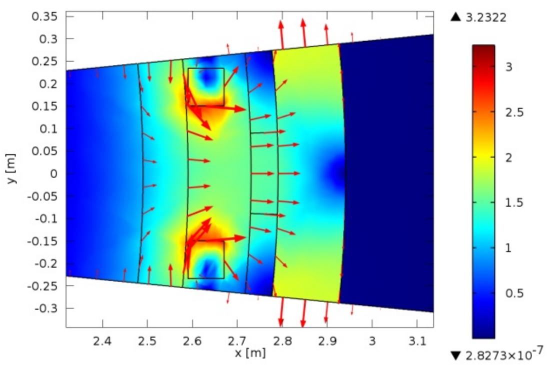

Figure 1. Modeled magnetic flux density in the cross section of a pole of a 10 MW direct drive generator with a coil engineering current density of 70 A/mm^2.

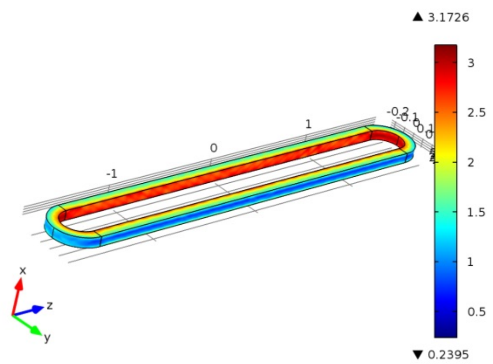

Figure 2. Modeled magnetic flux density of a race track coil in a 10 MW direct drive generator. This coils have the same cross section as the demonstration coil, but the length is 3.1 m.

4. Discussion

The load line reveals that operation at 20 K is not possible with the current design and the wire considered. However, at 10-15 K a sufficient margin to the critical current density of the tape appears attainable. The main properties of the generator are shown in table 2. The diameter and length of the generator are 6.0 m and 3.1 m. The magnetic flux density in the air gap is 1.5 T, notably higher than for a typical permanent magnet direct drive generator, but considerably lower than the LTS proposal of [3]. The usage of tape for a double pancake, a race track and the entire 32 pole generator are 1.5 km, 15 km and 474 km, respectively. Thus such a generator can be produced using the current piece length from the MgB_2 tape and wire production. The first estimate of the cost of the machine has been done on the basis of a tape cost of 4 €/m, which is expected to decrease to approximately 1 €/m after up-scaling. By additionally including the cost of active materials like copper and steel laminates, the cost of the active materials are estimated at 2.3 M€ or 226 €/kW (using 4 €/m). This is one of the main performance indicators, which are evaluated in the INNWIND.EU project for a 10-20 MW offshore turbine including blades, nacelle tower and offshore foundation. The cost per capacity of the direct drive generator should be below 20% of the total offshore turbine cost of 1.5 M€/ to be competitive with the gearbox solution. Hence, when comparing the 226 €/kW obtained for the modelled 10 MW generator with the 300 €/kW requirement, it can be seen that the MgB_2 based generator passes the initial cost criterion already at today's cost level of MgB_2 wire. Further work need to evaluate the cost of the cryostat and cooling system as well as finding the optimal amount of iron minimizing the cost (taking the weight into account). Additionally it should be mentioned that the development of MgB_2 wires is intensive, and a significantly better wire may be anticipated[8]. Looking at figure 3, it is notable that a 50 % increase of the critical current would allow for operation at 20 K and 3 T in an otherwise identical design[8].

Table 2. Properties of a 10 MW direct drive superconducting 32 pole generator based on MgB_2 race track coils with cross sectional dimensions equal to the small scale demonstration coil in table 1.

$R_{Fe\ out}$ [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 [%]		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 [€]	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)

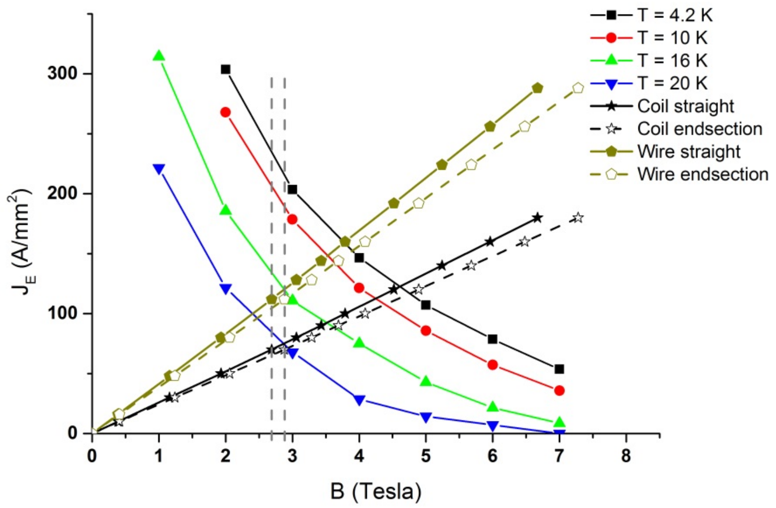

Figure 3. Load line of MgB_2 pole coil positioned in a 10 MW direct drive wind turbine generator. A coil J_{Ecoil} = 70 A/mm^2 is desirable and corresponds to a J_{Ewire} = 112 A/mm^2 taking insulation and spacers into account (crossing of vertical dashed line). The J_E of the wire includes the MgB_2 tape (3.0 mm x 0.5 mm) and a Cu strip for stabilization (3.0 mm x 0.2 mm) [7]. Operation at 2 T seems possible at 20 K whereas *T* = 10-15 K is needed for 3 T operation.

5. Conclusion

We have designed an MgB_2 race track coil intended for demonstration of a pole of a 10 MW direct drive wind turbine generator. The coil consists of 10 double pancake coils stacked into a race track coil with a cross section of 84 mm x 80 mm. The length of the straight section is 0.5 m and the diameter of the end sections is 0.3 m. It will produce magnetic flux density of about 1.5 T in the air gap of the 10 MW 32 pole generator and about 3.0 T at the edge of the superconducting coil with an operation current density of the coil of 70 A/mm^2. The load line proposal indicates that the operation temperature will be 10-15 K.

Acknowledgement
This work is done as part of work package 3 “Electro-mechanical conversion“ of the INNWIND.EU project funded under FP7. The work is part of the task 3.1. “Superconducting generators” - See www.innwind.eu for more information.

References
[1] Abrahamsen A B, Jensen B B, Seiler E, Mijatovic N, Rodriguez-Zermeno V M, Andersen N H and Østergård J, 2011 *Physica* C **471** 1464
[2] Snitchler G, Gamble B, King C and Winn P 2011*IEEE Trans. Appl. Supercond.* **21** 1089
[3] Fair R 2012 “Superconductivity for Large Scale Wind Turbines”, *DOE report* DE-EE0005143
[4] Mine S, Xu M, Buresh S, Stautner W, Immer C, Laskaris E T, Amm K and Grasso G 2013 IEEE Trans. Appl. Supercond. **23** 4601404
[5] Sætre F, Hiltunen I, Runde M, Magnusson N, Järvelä J, Bjerkli J and Engebrethsen E 2011 *Supercond. Sci. Technol.* **24** 035010
[6] DTU 10 MW reference turbine, http://www.hawc2.dk/ September 2013
[7] G. Grasso, private communication
[8] Rindfleisch M et. al.,2013, EUCAS conference 1M-WT-I1 , & Brisgotti S et. al., 2013, EUCAS conference 1M-WT-O1