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Design of MgB_2 race track coil for wind generator pole demonstration

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Introduction

Offshore wind power demands large turbines in order to drive down the cost of energy and superconducting direct drive generators have been suggested advantageous due to a better size scaling compared to permanent magnet technology for ratings above 10 MW[1]. The cost of the superconducting wires must however be sufficiently low to allow additional cost of the cooling equipment and to comply with the cost of energy of the electricity market. The trade-off between the price of the superconductor and the cooling system is often favoring a low temperature to utilize the superconductor current density and a high operation temperature to simplify the cooling system. Superconducting direct drive wind turbine generators have been suggested based on High Temperature Superconductor (HTS) YBCO tapes [2] and also on Low Temperature Superconductor (LTS) NbTi [3]. With a $T_C \sim 39$ K, MgB_2 provides an operation temperature window of T = 10-20 K above the usual operation temperature T = 4.2 K given by liquid helium for the LTS and below the operation window T = 25-27 K provided by the liquid neon cooling of the HTS superconductors. MgB_2 tapes and wires are produced by the powder in tube method, which is simpler and cheaper than the thin film technology used for the coated conductor HTS tapes. Secondly 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 a candidate for the field coils of wind turbine generators, but the large scale and in-field performance of the MgB_2 technology still needs verification.

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 B = 3-4 Tesla, corresponding to operation temperatures T = 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 (fig 1a). The coil is targeted at a demonstration in a cryostat equipped with a cryocooler with a base temperature of T = 10 K [5] (fig 1b). Conduction cooling is employed to extract the heat from the coil. Table 1 is listing a coil proposal layout based on a series of stacked double pan-cake coils insulated with Kapton tape and impregnated with Stycast. The amount of tape needed for the demonstration is about 4.5 km.

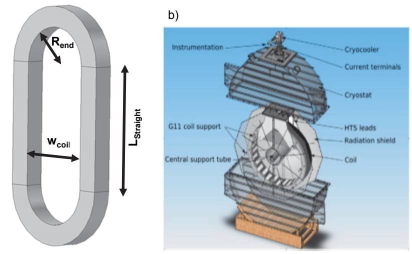
Direct drive 10 MW generator

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 (fig 1c) in order to comply with the specifications of the 10 MW INNWIND.EU reference turbine[6]. Figure 2a and b are showing the magnetic flux density distribution in the cross section of the pole and along the axial length of the pole at a coil current density of $J_{coil} = 70$ A/mm^2. The magnetic flux density at the coil reached B ~ 2.9 Tesla in the straight section and about 3.0 Tesla at the end section as shown in fig 2c. The corresponding load line is shown in fig 2d along with engineering current densities of the tape at different temperatures.

Discussion

The load line reveals that T = 20 K operation is excluded with the current design, whereas T = 10-15 K seem possible with a sufficient margin to the critical current density of the tape. The main properties of the generator are shown in table 2. The diameter and length of the proposed generator will be 6.0 m and 3.1 m. The magnetic flux density in the airgap is 1.5 Tesla being 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. Thus such a generator could be produced using the current piece length from the tape and wire production. The first estimate of the cost of the machine has been done on the basis of an expected tape cost of 4 €/m, which is expected to decrease to approximately 1 €/m after up-scaling and including learning. By additionally including the cost of active materials like Cu and steel laminates then the cost of the active materials are determined to be 2.3 M€ and 226 €/kW (using 4 €/m). This is one of the main performance indicators, which are evaluated in the INNWIND.EU project for a P =10-20 MW offshore turbine including blades, nacelle tower and offshore foundation. The cost per capacity should be below 20% of the offshore turbine cost of 1.5 M€/MW ~ 300 €/kW in order to be competitive with the gearbox solution. This is fulfilled and further work will be done to evaluate the cost of the cryostat and cooling system.

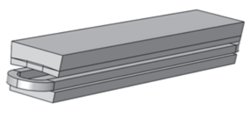
a) b)



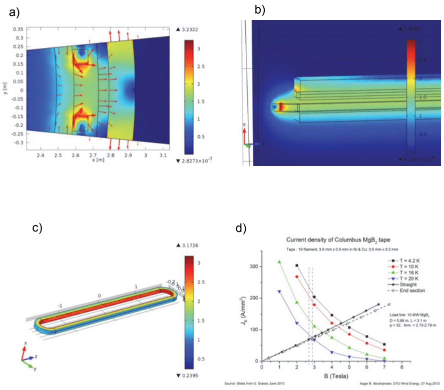
Length strait section: L_{strait} [m]	0.5
Opening inside pancake: W_{coil} [m]	0.3
Radius of end winding: R_{end} [m]	0.15
Number of turns in pancake layer	100
Thickness of MgB_2 tape: $T_{SC, tape}$ [mm]	0.7
Width of MgB_2 tape: $W_{SC, tape}$ [mm]	3.0
Thickness of insulation: $T_{insulation}$ [mm]	2*0.07 = 0.14
Width of insulation: $W_{insulation}$ [mm]	~ $T_{insulation} + T_{spacer}$ ~ 1.0
Thickness of pan cake (windings)T_{coil} [mm]	N * ($t_{tape} + t_{insulation}$) ~100 * (0.7 mm + 0.14) = 84 mm
Height of pan cake coil: H_{coil} [mm]	2*$W_{tape} + W_{insulation}$ ~2*3 mm + 1.0 mm = 7 mm
Length of tape in single pan cake: $L_{singlepancake}$ [m]	$L_{singlepancake}$ = $N \cdot [2 \cdot L_{strait} + 2\pi R_{end}] + 2\pi \cdot t_{wire} \cdot N(N+1)/2$ = 100· [2·0.5 m + 2π·0.15 m] + 2π·0.84 mm*100*101/2 = 100 m + 94.2 m + 26.6 m = 220.8 m
Length of tape in double pan cake: L_{DP} [m]	441.6 m
Spacer between double pancakes: $L_{coilspace}$ [mm]	1
Number of double pancakes $N_{pancakes}$	10
Coil assembly height [mm]	$N_{pancakes} \cdot [H_{coil} + L_{coilspace}]$ = 10·8 mm = 80 mm
Total tape usage $L_{tapetotal}$[m]	10·441.6 m = 4416 m
Field coil width [mm]	84
Field coil height [mm]	80
Race track filling factor A_{SC}/A_{coil} [%]	62.5

Table 1. Layout of MgB_2 demonstration coil

c)



a) b) c) d)



$R_{Fe\ out}$ [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 (→ 1)	M_{active} [kg]	52331
SC cost [k€]	1897 (→ 474)	Cost Cu [€]	291234
$M_{Superconductor}$ [kg]	7918.1	Cost Fe [€]	74994
$M_{cryostat+cooler}$ [kg]	TBD	Cost total [k€]	2263 (→ 840)
Price cryostat	TBD	Cost / cap. [€/kW]	226 (→ 84)

Table 2. Properties of MgB_2 10 MW wind generator

Conclusion

We have designed a MgB_2 race track coil intended for demonstrating a pole of a 10 MW direct drive wind turbine generator. The coil consist 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 strait section is 0.5 m and the diameter of the end section is 0.3 m. It will produce about 1.5 tesla magnetic flux density in the air gap of the 10 MW 32 pole generator and about 3.0 tesla 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 between T = 10-15 K.

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