Conceptual design and thermal analysis of a modular cryostat for one single coil of a 10 MW offshore superconducting wind turbine

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Abstract. Superconducting generators show the potential to reduce the head mass of large offshore wind turbines. A 10 MW offshore superconducting wind turbine has been investigated in the SUPRAPOWER project. The superconducting coils based on MgB_2 tapes are supposed to work at cryogenic temperature of 20 K. In this paper, a novel modular rotating cryostat was presented for one single coil of the superconducting wind turbine. The modular concept and cryogen-free cooling method were proposed to fulfil the requirements of handling, maintenance, reliability of long term and offshore operations. Two stage Gifford-McMahon cryocoolers were used to provide cooling source. Supporting rods made of titanium alloy were selected as support structures of the cryostat in aim of reducing the heat load. The thermal performance in the modular cryostat was carefully investigated. The heat load applied to the cryocooler second stage was 2.17 W@20 K per coil. The corresponding temperature difference along the superconducting coil was only around 1 K.

1. Introduction

The needs for high power offshore wind turbines are increasing continuously together with the rapid development of the wind power market. Superconductivity may be the only technology to scale wind turbines up to 10 MW and beyond by reduction of the nacelle mass. Accordingly, a superconducting 10 MW wind turbine concept for offshore applications is currently under development within the SUPRAPOWER project supported by EU FP7[1]. The project aims to provide an important breakthrough in offshore wind industrial solutions by designing an innovative, lightweight, robust and reliable 10 MW class offshore wind turbine.

The objective of this study is to design and optimize the cryostat for the superconducting wind turbine. The superconducting coils based on MgB_2 are supposed to work at about 20 K. Due to the requirements of handling, maintenance, reliability of long term and offshore operation, a concept of modular cryostat was proposed[2]. A cryogen-free cooling method using two stage Gifford-McMahon cryocoolers was selected[3]. The required low temperature difference between the coldest point at the cryocooler cold head and the warmest point at the coil part farthest from the cryocooler requires a special design for a support structure of the coil inside the cryostat and a very good thermal insulation.

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The support structures of the cryostat were thermally optimized in aim of reducing the heat load. With careful consideration of AC loss, heat transfer by radiation and conduction through support structure together with current leads, the thermal performance of superconducting coil was analyzed analytical and numerically with the use of the FEM tool Ansys[TM][4]. In this paper, the concept of the modular cryostat and results of thermal analysis are given in detail.

2. Superconducting wind turbine

The SUPRAPOWER project has developed a design concept of 10 MW superconducting wind turbine[1]. The solid model of the generator to mainframe design can be seen in Figure 1[5]. This generator overcomes the presented barriers for other superconducting concepts, being the design oriented to the offshore wind industry demands. The main advantages of this solution are the reduction of turbine head mass in about a 30 % with respect to conventional generators. The generator is a direct drive salient poles synchronous machine. It's a partially superconducting generator since conventional coils with copper wires at room temperature are implemented as the stator coils. Superconducting materials working at cryogenic temperatures are only applied in the field coils. Instead of using high temperature superconducting (HTS) materials, MgB_2 tapes are selected because they are an industrial solution with a very competitive cost, several times lower than other HTS wires. An MgB_2 field coil in the form of sandwich tape with outer copper stabilization layer has been specifically designed, manufactured and characterized for this generator.
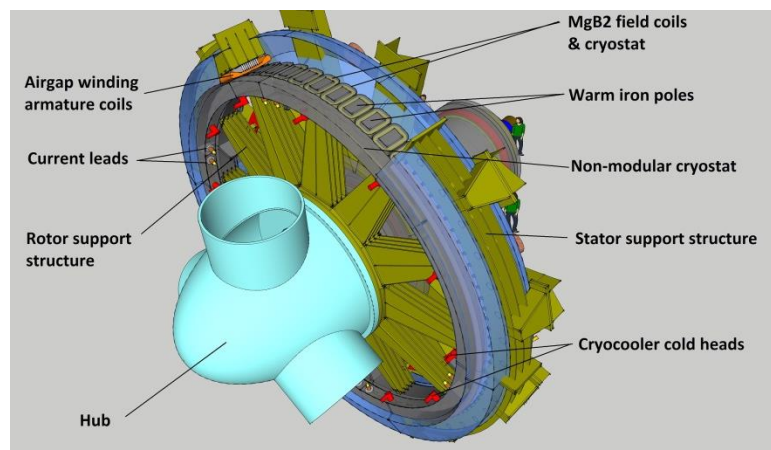

Figure 1. 10 MW SUPRAPOWER wind turbine concept

The superconducting part, which is different from the conventional generator, is supposed to be packaged in a cryostat normally in vacuum environment in order to keep function. In view of reducing the ambient to cryogenic temperature interfaces thus to decrease the heat load into the cryostat, the conventional conceptual design of the cryostat used for the superconducting generator adopts a single vacuum vessel for all the superconducting coils[6-9]. Nevertheless, when transforming the conceptual design to reality, the single vessel concept will lead to other practical problems to challenge the transportation, installation, maintenance and reliability of the large scale superconducting wind turbine. Therefore, the modular concept which atrracts more attention recently in large superconducting rotating applications[10,11] are introduced to the coil and cryostat in the SUPRAPOWER project in order to make transportation, installation and maintenance easier in spite of causing more heat load. Benefit from the modular design, the 10 MW superconducting generator concept can be validated through a minimum scale model of 500 kW, as shown in Figure 2. The scaled generator has been designed in order to show the feasibility of the novel conceptual superconducting 10 MW wind turbine. To keep the maximum similitude between the 10 MW generator and the scale generator, the power reduction is obtained by reducing the number of poles from 60 to 4 and maintaining the size of the superconducting rotor coils identical both in the full and the scale

generator. Typical full scale generator features like specific shear stress, superconductivity and cryogenic implementation, modularity, quench detection and torque transmission will be basically inherited. This yield to a scaled generator which fulfils the basic performance parameters of the 10 MW machine, but with a substantial reduction of diameter, weight and power, allowing testing it in conventional test benches. The main characteristics of the 10 MW superconducting generator and scaled machine are listed in Table 1.
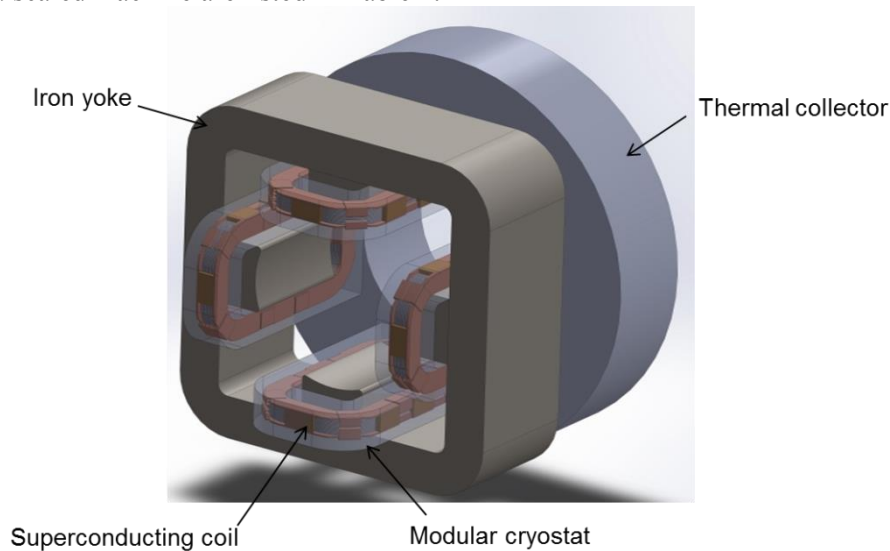

Figure 2. 500 kW SUPRAPOWER scale generator

Table 1 SUPRAPOWER generators specifications (10 MW and scale generator and demonstrator)

Parameters	10 MW generator	Scale generator
Number of poles	60	4
Rated power	10000 kW	550 kW
Rated speed	8.10 rpm	121.5 rpm
Rated torque	11.8 MN·m	45.502 kN·m
Air gap diameter	15 m	750 mm
Stack length	0.52 m	0.52 m

3. Conceptual design of the modular cryostat

The cooling system is an essential part of any superconducting applications. The superconducting coils of the wind turbine generator require one cryostat or cryostats per coil to keep the necessary low temperature with a low heat load. Tecnalia has proposed a concept of modular rotating cryostat as described in the early patent[2]. According to this cooling concept, the cryostat must be divided in two main parts: one modular cryostat able to accommodate a single coil and a thermal collector which links all the modules (see Figure 2). The modular cryostats will be the same for the 10 MW and scaled generator, but the thermal collector will be different in size for both generators. In this paper, we concentrated on the design and analysis of the modular rotating cryostat.

Figure 3 shows the schematic concept of modular cryostat design. The cryostat mainly includes vacuum vessel, active cooled shield, multi-layer insulation (MLI) and the connected support structures. The cryogenic cooling source of this supercoducting generator will be crycoolers since no cryogenic fluids is readily applicable in the 20 K working temperature of superconducting MgB_2 wires. Even though the liquid neon or gaseous helium could be used with high thermal performance[12], in order to seek for more compact design and simple operation, the cryogen free concept is chosen to accommodate the high reliability requirements originating from offshore applications. As shown in Figure 4, the heat load of the superconducting coil will be removed by commercial two stage Gifford-McMahon (G-M) cold heads r analysed otating together with the rotor seeing that preliminary tests of the rotating G-M cryocooler shows little performance degradation[13]. A cryogenic rotary joint will be specially designed to connect the stationary helium compressor and the rotating cold heads. The heat extraction will be done by conduction through two high conductivity thermal circuits made of copper (enclosed by the thermal collector). One of them will be connected to the cryocoolers first stage and to the active cooled shield (Temperature~80K), and the other one will be thermally linked to the second stage of the cryocooler and to the superconducting coils, keeping them to their operation temperature at about 20 K.

Due to limited space available for the cryostat, the vacuum vessel and active cooled shield of the cryostat are obliged to adopt rectangular shape, even though the circular shape is turned out to have the advantages of easy manufacturability, lower wall thickness and better insulation. The materials of vaccum vessel and shield are stainless steel and copper, respectively. The outer surface of the copper frame of the superconducting coil will be polished in order to reduce the heat flux by radiation. Approximately 20 layers of MLI will be installed on the active cooled shield, and no MLI will be applied on the coil in order to save space.

The support structure is the key component of this modular cryostat, several different support ways have been proposed and investigated. As shown in Figure 3, the connection from active cooled shield to the superconducting coil and from shield to the vacuum vessel both finally adopt small rods as support structures. The supporting rods are divided into several units locating distribute along the cryostat. Each unit contains eight distributed straps, as can be seen in Figure 3. This arrangement is proposed to transmit the mechanical load of the superconducting coil under rotating conditions. Even though the supporting rods with material G10 has the lowest heat conduction, the metal material of titanium alloy Ti-6A1–4V is finally chosen for the cryostat supporting rods by compressively evaluating the heat conductivity, required volume, manufacturability and vacuum performance.
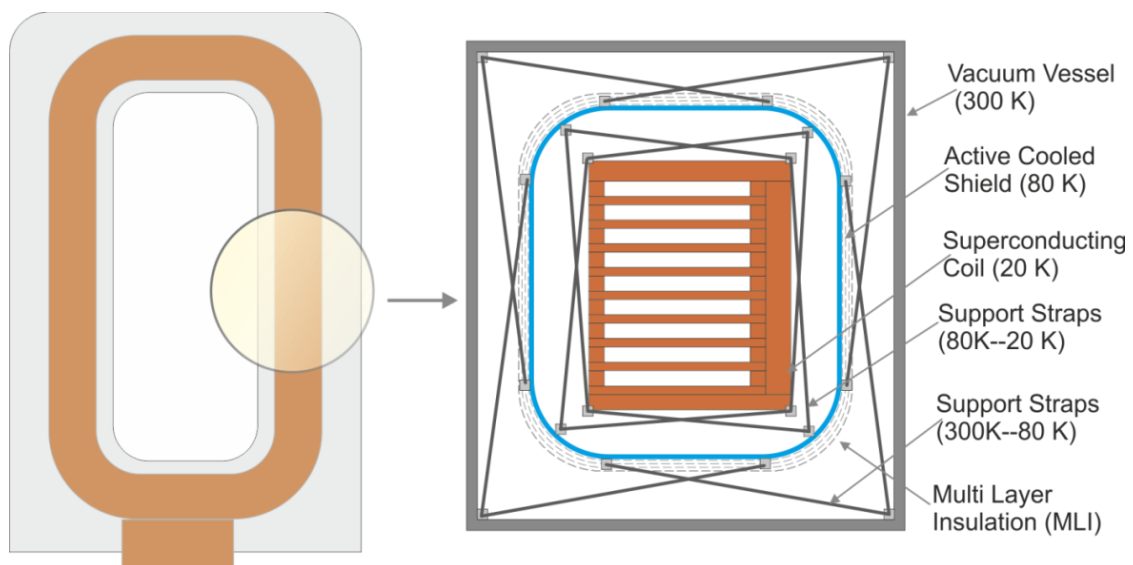

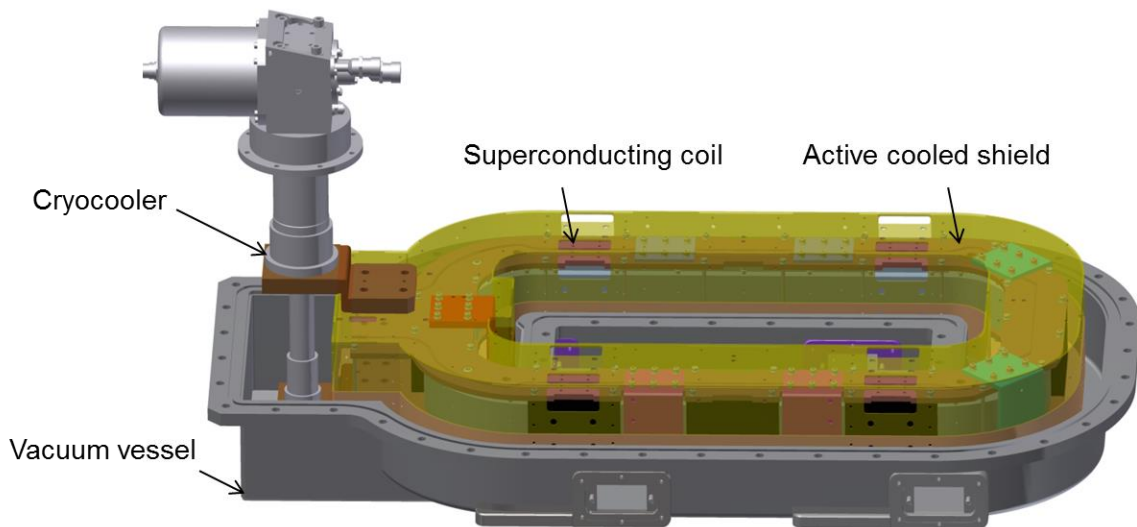Figure 3. Cross sectional view of the modular cryostat design

Figure 4. Solid model of the modular cryostat design

4. Thermal analysis

4.1. Heat load

Figure 5 shows the schematic energy balance of conduction-cooled superconducting coil by two-stage cooling inside the modular cryostat. In order to simplify the thermal analysis, assumptions are made as below:

- **Steady state**: The temperature of vacuum vessel, shield and coil are kept constant as 300 K, 80 K and 20 K, respectively.
- **Zero dimension**: There is no temperature difference along the shield and superconducting coil.
- **Neglect thermal anchor** : The thermal conductance of thermal anchor are high enough to make
$$Q_a = Q_c.$$

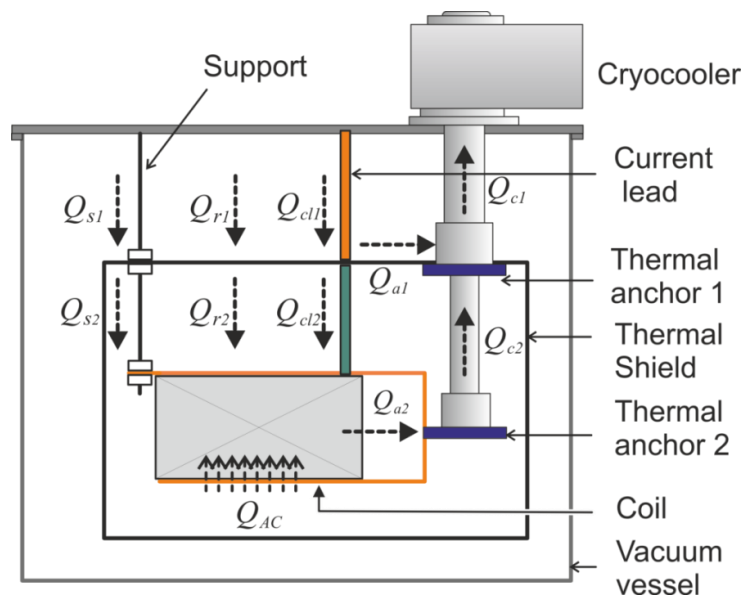Figure 5. Ilustration of heat flow inside the modular cryostat

Thus, based on first law of thermodynamics, the energy balance could be applied to the thermal shield and superconducting coil:

$$0 = Q_H - Q_L - Q_{c_1} \tag{1}$$
$$0 = Q_L - Q_{c_2} \tag{2}$$

Q_H represents the cryogenic heat load from ambient temperature T_a, to the shield temperature T_s (equal to first-stage temperature of the cryocooler 80 K). Q_L means the cryogenic heat load from T_s to the superconducting coil temperature T_{SC} (equal to second-stage temperature of the cryocooler 20 K). The heat load Q_H and Q_L in the cryostat are continuously generated by alternative current (AC) loss Q_{AC}, support conduction, Q_s, thermal radiation, Q_r, and heat through current leads, Q_{cl}.

$$Q_H = Q_{s1} + Q_{r1} + Q_{cl1} \tag{3}$$
$$Q_L = Q_{s2} + Q_{r2} + Q_{cl2} + Q_{AC} \tag{4}$$

Where subscripts 1 and 2 of Q's indicate the heat leakage from T_a to T_S, and T_S to T_{SC}, respectively. The heat flow through support structures are thermal conduction calculated by Fourier's law:

$$Q_s = N \frac{A}{L} \int_{T_L}^{T_H} k(T) \, dT \tag{5}$$

Where N and L are the number and length, respectively, of mechanical support of the cryostat. In Eq. (5) $k(T)$ is the temperature-dependent thermal conductivity of mechanical support, which in our case is made of titanium alloy Ti 6Al-4V.

We assume a radiative heat flux of 1 W/m^2 through more than 20 layers MLI from 300 K to 80 K. In addition, the heat flux of 0.1 W/m^2 with 10% reduction is used for the radiation from 80 K to 20 K. The total surface area for one coil considered for radiation is approximately 0.97 m^2 and the total surface area of the shield for radiation is 1.07 m^2.

The current leads will be divided in two parts: one is from 300 K to 80 K and the other is from 80 K to 20 K. The first part will be resistive DHP copper tubes, where the total heat is the sum of the dissipated by Joule effect plus the heat conducted from 300 K. For optimized current leads, the heat transmitted Q_{cl1} is only the one dissipated in the lead itself, being zero the one conducted from outside [14]. Its value can be calculated with the expression (6), valid only for materials following the Wiedemann-Franz law and in vacuum conditions, where L_0 is the Lorentz number and I lead design current. The nominal current for the Scale generator and the 10 MW machine is of 95 A. However, the current leads have been dimensioned for 120 A, in order to be able to test the SC coils above the nominal current.

$$Q_{cl1} = I \sqrt{L_0 (T_a^2 - T_s^2)} \tag{6}$$

The second part will be HTS wire and only heat conduction is calculated using Eq. (5) as Q_{cl2}.

Table 2 shows the calculated heat loads of the modular cryostat based on the analysis described above. The AC loss is obtained by additional electromagnetic FEM numerical simulation with the commercial software MAXWELL (part of the ANSYS package)[4]. The origin of the AC losses is the harmonic content of the AC current circulating through the resistive armature in the stator. The load supposed for the calculation is a resistor bank connected to the stator armature winding delivering

nominal power. Indeed, the magnetic field created by the fundamental frequency looks stationary in the rotor frame, but this is not the case for the field created by its harmonics, which will produce Eddy current losses. The simulation was performed in 2D taking into account the eddy currents induced in the most massive metallic parts around with higher field. It is worth to mention that after preliminary calculations, the superconductor magnetization losses yield negligible compared to the Eddy current losses. Conclusively, the overall heat load from the superconducting wind turbine to the first and second stage of the cryocooler is 8.26 W and 2.17 W, respectively.

Table 2. Calculated heat loads of the modular cryostat

	subscript	Q_s	Q_r	Q_{AC}	Q_{cl}	Q_a	T_a
Unit		W	W	W	W	W	K
Shield	1	5.11	1.07	0	3	8.26	80
Coil	2	0.79	0.1	1.25	0.03	2.17	20

4.2. Thermal performance

The temperature gradient of superconducting coil was highly concerned with respect to the critical temperature of MgB_2 wire. Thus, a three dimension numerical analysis of the demonstrator including four superconducting coils was performed with ANSYS. Two kinds of heat load were considered as boundary conditions: heat conduction and radiation. The overall heat load obtained from last section except radiation was taken into account as conduction applied to the coil. Because of the symmetry boundary condition, only half structure of the demonstrator was studied. The temperature distribution of the coils with the thermal collector ring at 20 K is shown in Figure 7. The cold end of 20 K is connected to the second stage of GM cooler. As shown in Figure 6, the maximum temperature is 20.99 K with a corresponding temperature difference of 0.99 K.
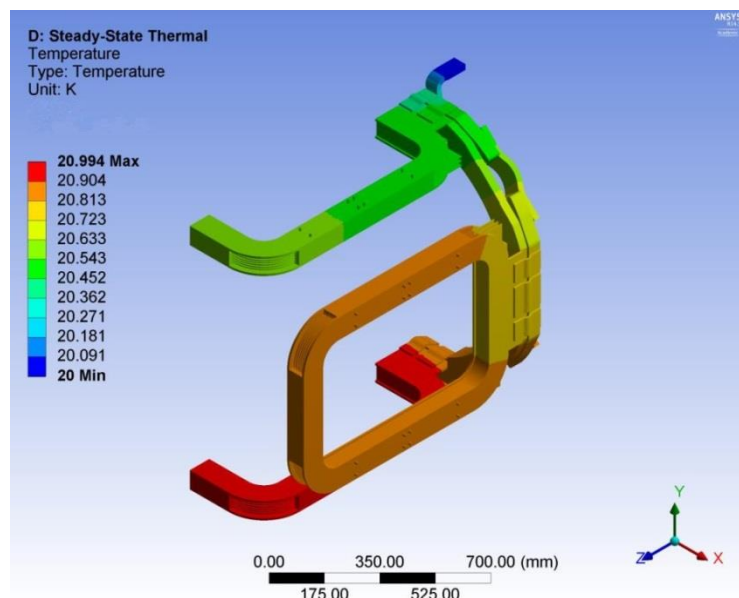

Figure 6. Temperature distribution of the superconducting coil in the scale generator

5. Conclusion

The modular rotating cryostat for one single coil of a 10 MW offshore superconducting wind turbine was successfully designed. The cryogen free cooling system will significantly enhance the reliability

and reduce the maintenance of the wind turbine. Thermal analysis proves that the modular cryostat could fulfil the working requirements of superconducting coil made of MgB_2. This modular cryostat is being manufactured and will be experimentally tested to verify the numerical analysis.

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