Preliminary test of the prototype modular cryostat for a 10 MW offshore superconducting wind turbine

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Abstract. The SUPerconducting Reliable lightweight And more POWERful offshore wind turbine (SUPRAPOWER), an EU FP7 funded research project, are under development for an innovative superconducting 10 MW class offshore wind turbine. Due to the requirements of handling, maintenance, reliability of long term and offshore operation, the cryostats are divided in two major parts: the modular cryostat able to accommodate a single coil and a thermal collector that links all the modules. The prototype modular cryostat was designed, manufactured and assembled in Karlsruhe Institute of Technology (KIT). The paper reports preliminary test results of proto-type modular cryostat with a two-stage Gifford-McMahon (GM) cryocooler.

1. Introduction

Huge offshore market is expected for the upcoming years once the cost will be further reduced. In order to improve the efficiency, offshore industry finds interest for large-scale wind turbines [1]. The conventional type is very challenging as the power is scaled up. Superconductivity may be the only technology to scale wind turbines up to 10 MW and beyond by reducing the nacelle mass [2]. Accordingly, a superconducting 10 MW wind turbine concept for offshore applications is currently under development within the SUPRAPOWER project supported by EU FP7 [3, 4]. The project aims to design an innovative, lightweight, robust and reliable 10 MW class offshore wind turbine and provide an important breakthrough in offshore wind industrial solutions.

The cryogenic cooling system, aiming to ensure the necessary working temperature with a low heat load for the superconducting (SC) MgB₂ coil, is an essential part of the superconducting wind turbine developed in the SUPRAPOWER project. The objective of Karlsruhe Institute of Technology (KIT) within this project is to develop a rotating modular cryostat concept and to build and validate one of these modules for cooling SC coils, working in the rotor of a synchronous salient poles generator. Following the cryogen-free concept, the cryogenic cooling system is mainly composed of three parts: cryocooler system, cryostat and specially designed coil formers [5]. During the second period of the project, based on viability of Tecnalia rotating cryostat concept, the conceptual design of the rotating cryostat for the 10 MW superconducting wind turbine has been developed. The cryostat consists of two major parts: one modular cryostat able to accommodate a single coil and a non-modular cryostat (also named as thermal collector) which links all the modules. As an intermediate step before the

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detailed design and manufacturing of the scale generator cryostat is carried out, a prototype modular cryostat has been manufactured, assembled and preliminary tested in KIT. This paper describes the design and initial test results of this modular cryostat.

2. Design of the modular cryostat

The SUPRAPOWER project are developing and validating a design concept of 10 MW superconducting wind turbine [3], based on the patent (PTC/ES2009/070639) hold by Tecnalia since 2009 [6]. The solid model of the generator to mainframe design is illustrated in Figure 1a [7]. This generator overcomes the presented restriction on other superconducting concepts for the design oriented to the offshore wind industry demands. The main advantage of this solution is the reduction of turbine head mass in about a 30 % with respect to conventional generators.

In order to make transportation, installation and maintenance easier, the coil and cryostat in the SUPRAPOWER project have adopted the modular concept which attracts more attention recently in large superconducting rotating applications [8, 9]. The modular concept will lead to additional heat load by increasing the ambient to cryogenic temperature interfaces. Nevertheless, benefit from the modular design, the 10 MW superconducting generator concept can be validated through a minimum scale model of 500 kW SC generator, as shown in Figure 1b. The scaled generator has been designed in order to show the feasibility of the novel conceptual SC 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 48 to 4 [4]. The size of the superconducting rotor coils are identical both in the full and the scale generator. The scale generator has the similar features as full scale generator like specific shear stress, superconductivity and cryogenic implementation, modularity, quench detection and torque transmission.

![Figure 1. Conceptual design of (a) the 10 MW SUPRAPOWER wind turbine; (b) the 500 kW SUPRAPOWER scale generator](image)

The prototype modular cryostat for validation was manufactured based on the design mode as shown in Fig.2. The prototype modular cryostat mainly includes vacuum vessel, active cooled shield, multi-layer insulation (MLI, not shown in Fig.2) and the corresponding support structures. Due to limited available space for the cryostat, the vacuum vessel and active cooled shield of this modular cryostat are both obliged to adopt rectangular shape, even though the circular shape has the advantages of easy manufacturability, lower wall thickness and better insulation. The materials of vacuum vessel and shield are stainless steel and copper, respectively. The active cooled shield is made of copper plate with 3 mm thickness. Some additional copper plates are attached on the shield to enhance the strength of the active cooled shield.
The support structure as illustrated in Fig. 2 is the key component of the modular cryostat. The connections from the active cooled shield to the superconducting coil and from the shield to the vacuum vessel both adopt small rods as support structures. The supporting rods between shield and superconducting coil are divided into four units distributed along the cryostat as illustrated in Fig. 2. Each unit contains eight rods. There is one pair of rods in each direction per unit in order to transmit the electric-magnetic (EM) force suffered by the superconducting coil under rotating conditions [10]. Even though the supporting rods with material G10 has the lowest heat conduction, the titanium alloy metallic material Ti-6Al–4V was finally chosen for the cryostat supporting rods by taking into account the heat conductivity, required volume, manufacturability and vacuum performance.

The prototype modular rotating cryostat are modified to integrate the two-stage GM cryocooler inside, as shown in Fig. 3. The first stage of cryocooler cold head is used to cool down the active cooled shield to a temperature around 80 K through copper thermal anchor. The second stage will be linked to the superconducting coils, maintaining them at their operation temperature about 20 K. The cryocooler are connected with flexible copper bridges, which act as thermal anchor fitting the displacement caused by the thermal contractions.
3. Numerical simulation

In order to predict the required time to cool down the prototype modular cryostat from ambient temperature to the operating temperature, a numerical model was established to perform the transient simulation. Fig. 4 shows the schematic energy balance of conduction-cooled coil by two-stage cooling inside the modular cryostat. Following the first law of thermodynamics, the energy balance of the modular cryostat system will be:

\[
\frac{d}{dt}(\rho V c_p T)_S = Q_H - Q_L - Q_{A_1} \tag{1}
\]

\[
\frac{d}{dt}(\rho V c_p T)_{SC} = Q_L - Q_{A_2} \tag{2}
\]

\[
\frac{d}{dt}(\rho V c_p T)_{A_1} = Q_{A_1} - Q_{C_1} \tag{3}
\]

\[
\frac{d}{dt}(\rho V c_p T)_{A_2} = Q_{A_2} - Q_{C_2} \tag{4}
\]

Where \( \rho, V, c_p \) and \( T \) are the density, volume, specific heat and temperature at constant pressure of each component, respectively. The subscripts \( S \) and \( SC \) denote the active cooled shield and superconducting coil. The heat transfer \( Q \)'s in Eqs. (1) and (2) will be described in detail in the following.

![Figure 4. Energy balance of prototype modular cryostat with two-stage cooling](image)

In Eq. (1) \( Q_H \) represents the cryogenic heat load from ambient temperature \( T_h \), to the shield temperature \( T_S \). \( Q_L \) means the cryogenic heat load from \( T_S \) to the superconducting coil temperature \( T_{SC} \). The heat load \( Q_H \) and \( Q_L \) in the cryostat are continuously generated by support conduction \( Q_s \), thermal radiation \( Q_r \), and heat through current leads \( Q_{cl} \).

\[
Q_H = Q_{s1} + Q_{r1} + Q_{cl1} \tag{5}
\]

\[
Q_L = Q_{s2} + Q_{r2} + Q_{cl2} \tag{6}
\]

Where subscripts 1 and 2 of \( Q \)'s indicate the heat leakage from \( T_h \) to \( T_S \), and \( T_S \) to \( T_{SC} \), respectively.

The heat flow through support structures are thermal conduction calculated by Fourier's law:

\[
Q_s = N \frac{A}{L} \int_{T_L}^{T_H} k(T) \, dT \tag{7}
\]

Where \( N \) and \( L \) are the number and length, respectively, of mechanical support of the cryostat. In Eq. (7) \( k(T) \) is the temperature-dependent thermal conductivity of mechanical support, which in our case is made of titanium alloy Ti 6Al-4V.
The heat transfer by thermal radiation to a body at temperature $T_L$ from the enclosed surface at temperature $T_H$ can be approximately estimated by [11]

$$Q_r \approx \frac{\sigma (T_H^4 - T_L^4)}{1 - \frac{1}{\varepsilon_H A_H} + \frac{1}{A_L} \left( \frac{1}{\varepsilon_L} + \frac{2N}{\varepsilon_N} - N \right)} \quad (8)$$

Where $A$ is surface area, $\sigma$ is the Stefan–Boltzmann constant and $\varepsilon$’s are the emissivity of the surfaces. $N$ is the number of multi-layer-insulation (MLI) installed between two surfaces.

Under high vacuum gas conduction is significantly very small comparing with other contributions for the heat load, and thus to be neglected in the numerical simulation. Moreover, a dummy coil with no current leads will be tested inside the modular cryostat. Therefore, the heat load caused by current leads will also not be taken into account. The heat conduction from two thermal anchors to shield and coil, could be calculated using Eq. (7). We also neglect the variation of density as function of temperature. With these considerations listed above, the overall governing equation of temperature for thermal shield, superconducting coil and two thermal anchors could be simplified.

The values of parameters used for the numerical simulation are listed in Table 1. The initial ambient temperature (boundary condition) is set as 300 K. Heun’s method is used to make the time discrete during cooling down. Adaptive time steps are applied in different temperature ranges. The simulation results will be compared with the experiment results and shown in the latter section.

Table 1. The value of parameters used for the numerical simulation

| Items               | Coil | Shield | Anchor1 | Anchor2 | Vessel | MLI |
|---------------------|------|--------|---------|---------|--------|-----|
| $m$ (kg)            | 142  | 60     | 2.49    | 1.59    |        |     |
| Surface area (m$^2$)| 0.97 | 1.47   |         |         | 1.52   |     |
| Support diameter (mm)| 4.5  | 4.5    |         |         |        |     |
| Support numbers     | 32   | 32     |         |         |        |     |
| Support length (mm) | 122  | 162    |         |         |        |     |
| Connection length (mm)| 125  | 122    |         |         |        |     |
| Connection area (cm$^2$)| 18   | 22     |         |         |        |     |
| MLI layers          | 10   | 20     |         |         |        |     |
| Emissivity$^2$      | 0.02 | 0.02   | 0.07    | 0.03    |        |     |

4. Experiment setup

The superconducting coil was developed in parallel with the modular cryostat, and the manufactured cryostat was finished before the production of the coil. Therefore, as shown in Fig. 2, a dummy coil made of copper was designed and manufactured in advance to perform as the cold mass. The dummy coil including two thick copper plates has the similar dimension as the real superconducting coil developed in the SUPRAPOWER project.

Since the manufacturing of the modular cryostat has been delayed and lag behind the schedule, we carried out first preliminary test of the modular cryostat to permit the project progress. As shown in Fig. 5, four calibrated carbon ceramic TVO temperature sensors with 1% uncertainty are located in the dummy coil to measure the temperature profile. One calibrated TVO sensor is installed in the thermal anchor to the first stage of the cryocooler and another TVO sensor is mounted in the thermal anchor to
the second stage of the cryocooler. Temperature sensor and heater are not installed on the active cooled shield.

![Cryocooler diagram](image)

**Figure 5. Instrumentation diagram of the prototype modular cryostat**

5. Results and discussions

Fig. 6 shows both the measured and simulated temperature profile versus time during cooling down of the cryostat. In order to validate the preceding simulation results, the temperature of 1st stage thermal anchor $T_{a1}$ ($T_5$), 2nd stage thermal anchor $T_{a2}$ ($T_6$) and coil temperature $T_{sc}$ ($T_1$) are selected. As shown in Fig. 7, the dotted lines represent simulation results while the solid lines represent experiment results. During the experiment, it took about 20 hours for the first stage thermal anchor to reach the lowest temperature, which is around 33 K. The second stage thermal anchor together with the linked dummy coil required 56.5 hours to reach the lowest temperature, which was around 9.8 K and 9 K respectively.

By comparing the experiment and simulation results, there are certain agreements between them:

- Simulated lowest temperatures are nearly the same with the experiment results.
- The trends of simulated cooling down curve agree with the experiment results.

However, there are also some distinction between simulation and experiment results:

- The shape of simulated cooling down curve of 1st stage thermal anchor is steeper than the experiment results.
- The experiment requires more time for the coil to reach the lowest temperature. The exceed time is around 7.5 hours

However, one problem was detected: the second stage thermal anchor temperature was unexpectedly larger than the dummy coil temperature. In principle, the thermal anchor should be colder than the dummy coil since it is closer to the second stage cold head, where the cooling power is generated. In order to check this issue, the temperature profile during the steady state long time operation was also monitored as shown in Fig. 7. The measured temperatures of the four temperature sensors located in the dummy coil were basically coincident. The temperature difference between the four temperature sensors is less than 0.01 K. It provides the cross check and indicates that the measured coil temperature is trustable. Therefore, the problem is supposed to be occurred in the temperature sensor located in the second stage thermal anchor. It was checked that neither the acquisition program nor the corresponding calibration curve was the problem reason. Furthermore, there is a constant temperature difference of 0.8 K between the thermal anchor and the coil, registered
simultaneously, showed in Fig. 7. As a result, we think that this problem may be attributed to an imperfect installation of the temperature sensor in the second stage thermal anchor, which leads to a contact resistance between the sensor and the copper block. Therefore, the actual reason will be investigated by disassembling the cryostat after the preliminary experiment.

![Temperature Profile](image1.png)

Figure 6. Measured and simulated temperature profile during cooling down of the modular cryostat

Conclusively, the comparison validates the availability of the numerical code on one hand. Nevertheless, on the other hand, the numerical code needs to be further checked based on the experiment results. There are many approximations when fitting the load map of the cryocooler. Inspired by the experiment results, sectional load map will be chosen in the following simulations, hence more precise fit of the cooling power load map will be used at low temperatures.

Moreover, as shown in Fig. 7, the dummy coil temperature is not stable during the long time operation. The temperature vibrates in a certain range, which is around 0.5 K for the dummy coil and 0.4 K for the second stage thermal anchor. The instability of temperature is ascribed to the cryocooler cold head. The motion of the displacer of the GM cryocooler produces a periodic temperature vibration. The influence of this temperature vibration on the performance of superconducting coil needs to be further investigated.

![Temperature Vibrations](image2.png)
Figure 7. Measured long time temperature profile during operation after cooled down

6. Conclusion
The modular rotating cryostat for one single coil of a 10 MW offshore superconducting wind turbine was preliminary tested at KIT. The dummy coil could reach a cryogenic temperature of 9 K after 56.5 hours. This encouraging experimental result agrees well with simulation which validated the design of the modular cryostat and especially the innovative support structures.

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References
[1] Marloes C, Mark H, Hans-Joerg A, Annette K and Stefanie H 2012 *Environ. Sci. Technol* **46** 4725
[2] Abrahamsen A B, Mijatovic N, Seiler E, Zirngibl T, Træholt C, Nørgård P B, Pedersen N F, Andersen N H, and Østergård J 2010 *Supercond. Sci. Technol* Superconducting wind turbine generators **23**, 3
[3] Sanz S, Arlaban T, Manzanas R, Tropeano M, Funke R, Kováč P, Yang Y, Holger N, and Mondesert B 2014 *J. Phys. Conf. Series* Superconducting light generator for large offshore wind turbines **507** 032040
[4] Iker M, Ainhoa P, Gustavo S, Santiaog S, Jose M, Matteo T, Jiuce S and Canosa T 2016 *Supercond. Sci. Technol* Lightweight MgB2superconducting 10MW wind generator **29** 024005
[5] Jiuce S, Santiago S and Holger N 2015 *Proc. DKV 2015* Modular cryostat for a 10 MW offshore superconducting wind turbine
[6] Sarmiento G, Merino J M, Garcia-Tejedor J, Ibañez P and Apiñaniz S 2012 *European Patent Application* Direct-action superconducting synchronous generator for a wind turbine PCT/ES2009/070639
[7] Pujana A, Merino J M, Sarmiento G, Sanz S, Marino I and Villate J L 2014 *The European Wind Energy Association* Design, optimization and integration of a direct drive superconducting generator for large wind turbine
[8] Keyssan O and M. Mueller 2015 *Supercond. Sci. Technol* A modular and cost-effective superconducting generator design for offshore wind turbines **28** 3
[9] Yamasaki H, Natori N, and Furuse M 2015 *IEEE Trans. Appl. Supercond* Evaluation of Heat Inleak in a Model Superconducting Coil Module for a Wind Turbine Generator With Iron Cores **25** 3
[10] Jiuce S, Santiago S and Holger N 2015 *IOP Conf. Series: Materials Science and Engineering* **101** 012088
[11] Yeon C, Dong K and Dong S 2012 *Cryogenics* Optimal cool-down time of a 4 K superconducting magnet cooled by a two-stage cryocooler **52** 13