



Electrical and thermal characterization of a novel high pressure gas cooled DC power cable

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ABSTRACT

High-temperature superconductors (HTS) allow power cables of substantially higher current density than conventional copper or aluminum cables. This is important for applications where a low mass and a low volume are critical such as naval, aeronautical and space applications. The novel type of cable under consideration is cooled by gaseous Helium at elevated pressure. Helium is known for having poor electric breakdown strength; therefore the dielectric capabilities of this type of cable must be tested under conditions similar to the envisaged operation. In order to study the dielectric performance we have designed and built a novel high pressure cryostat rated at 2.17 MPa which has been used for testing model cables of lengths of up to 1 m. The cryostat is an open system where the gas is not re-circulated. This allows maintaining a high purity of the gas. The target temperature range is between 40 K and 70 K. This substantially increases the critical current density of the HTS compared to 77 K, which is the typical temperature of cables cooled by liquid Nitrogen. The cryostat presented allows for adjusting the temperature and keeping it constant for the time necessary to run a complete dielectric characterization test. We give a detailed description of the cryostat. Measurements of partial discharge inception voltages as well as the temperature distribution along the model cables as a function of time are presented. Tests showed that the thermal insulation characteristics of this cryostat were sufficient for the dielectric tests of up to 1 h duration. The partial discharge inception voltage (PDIV) of the high voltage bushing was about 16 kV. These values are well within our design requirements.

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1. Introduction

Terrestrial systems for transmission and distribution of electrical power are dominated by conductors made of copper or aluminum. Such conductors have limited capabilities regarding maximum current density, typically around 0.5–10 A/mm². The current density is limited not only by the conductor itself but also by the capabilities of the power system to remove heat due to ohmic losses in the conductor. High power applications therefore are required to have conductors of large cross-sectional areas together with high system voltage levels. The latter requires substantial amounts of insulation material. This is unfavorable for naval, aeronautical and space applications where high power density by volume and mass are of utmost importance. High-temperature superconductors (HTSs) are considered an option [1] as they would allow power cables of substantially higher current density. According to Haugan et al., a reduction of

mass of approximately 80 kg/m length and a reduction of volume by a factor of ten can be achieved by replacing a 270 V/20 kA copper cable by an HTS cable of equivalent rating [1].

The drawback is: HTS power cables need to be cooled to cryogenic temperatures. The standard method of cooling is based on liquid Nitrogen. This limits the lower limit of operating temperature to 63 K (melting point of Nitrogen). The critical current of HTS materials increases significantly as they are cooled to lower temperatures, which further increases the power density. Gaseous Helium allows operating temperatures below 63 K with additional benefits, such as omission of phase changes, lower risk of asphyxiation if operated in confined spaces and wider operating temperature range. Fitzpatrick et al. [2] and Kephart et al. [3] have described a Helium gas cooled HTS degaussing system for Navy shipboard application. The optimum operation temperature for this application was reported to be 55 K.

Among the disadvantages of gaseous Helium is the low dielectric strength compared to liquid Nitrogen, even when operated at elevated pressure levels. It is critically important to ensure high dielectric integrity of the HTS cable, where the Helium serves both as the coolant and forms an important integral part of the dielectric

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system of the cable together with several layers of polymeric tape. This needs a conservative design regarding maximum electric field and careful dielectric characterization by laboratory tests. Therefore, the primary aim in this project is to study the dielectric characteristics of the insulation system. The project deals with a superconducting cable operating under DC voltage capable of carrying high power. Results of these dielectric studies will provide the necessary data for the design and manufacture of a 30 m monopole DC cable rated at 1 kV, 3 kA operating in gaseous Helium at between 40 K and 70 K at a maximum pressure of 2.17 MPa.

An essential apparatus for the study of dielectrics at cryogenic temperatures is a well-designed and fabricated cryostat. The conditions under which the dielectric studies are to be conducted is determined by the final application, hence it dictates the final form of the cryostat. Previous studies in Helium [4] had utilized a high pressure vessel containing the electrodes which was immersed in a cryostat that contained a pool of liquid Helium at the bottom of their cryostat. In the present work we have designed and built a cryostat that can be pressurized up to 2.17 MPa where the medium is purely gaseous Helium and we are able to achieve temperatures of between 40 K and 77 K on the test object at various pressure levels. The essential difference is in the present work there was no liquid helium present in the high pressure cryostat when the experiments are conducted.

We define a figure of merit for the cryostat based on the following parameters: Consumption of liquid Helium, rate of rise of temperature on the test object (in this case it is the model cable) and the inception voltage level of partial discharge of the high voltage bushing which forms part of the cryostat.

2. Experimental setup

2.1. High pressure cryostat

Fig. 1 shows a schematic diagram of the high pressure cryostat (manufactured by Technifab Products of Indiana) that has been used for all experiments reported in the present work. The innermost enclosure of the pressure vessel is rated at 2.17 MPa. Its inner dimensions are, diameter 265 mm and height 1.5 m. The pressure vessel is surrounded by a vacuum jacket which contains a liquid Nitrogen jacket for radiation shielding. The vacuum jacket was maintained at around 100 μ Pa. The lid of the cryostat is dome shaped and double walled with a vacuum space between the walls. This vacuum space was also maintained at a similar pressure level to the other one. The lid carries seven ports, six of which are DN40 flanges (2.75 in. ConFlat) and one is DN100 (6 in. ConFlat). The largest of the ports on the lid is situated centrally and carries the high voltage bushing. The others are spaced evenly around the central port. They were utilized for pumping, exhausting, liquid Helium admittance, pressurized gas input and instrumentation. The lid and the cryostat are joined through a large flange. Fig. 2 shows a picture of the cryostat.

2.2. The HTS model cable

The test object was a 1 m long model cable rated at 1 kV DC. It consists of a stainless steel former on which are wound a number of copper conductors of the same dimensions as HTS conductors, which will be used for the final design. Here, the emphasis was on the dielectric properties of the cable, therefore no expensive HTS tape was used. The insulation was in tape form, which was spiral wound. Butt gaps in the winding were unavoidable and got filled by the cooling medium, which was Helium. An aluminum ground shield was wound over the insulating layers and connected

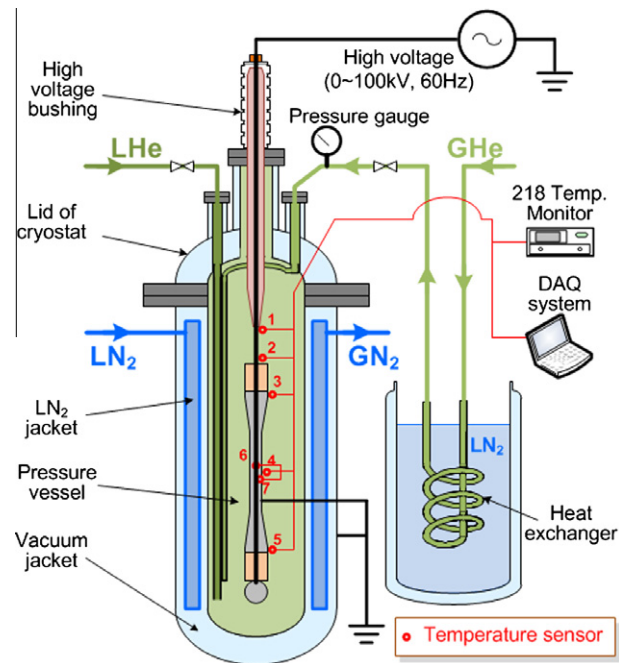


Fig. 1. Schematic diagram of the high pressure cryostat and temperature sensor locations.

to ground potential. Each end of the cable carried a stress cone in order to reduce the electric field at the termination points.

2.3. Partial discharge measurement method

Partial discharge (PD) has a detrimental effect on the dielectric and therefore is an important parameter in the operation of any type of cable. The inception voltage of PD has to be well above the maximum operating voltage of the cable. Even though the demonstration cable under consideration will operate under DC voltage, we consider PD characterization an important design

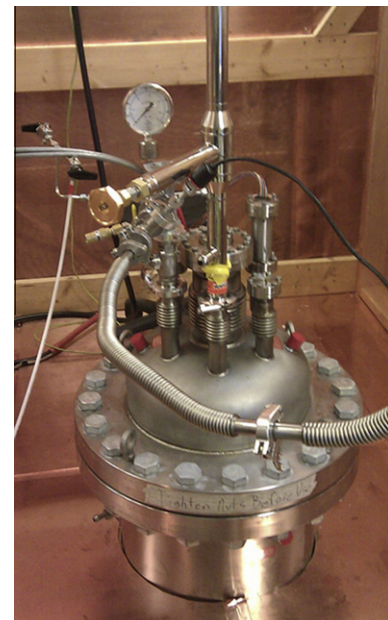


Fig. 2. Photograph of cryostat. The flexible steel hose connects the pressure vessel with the vacuum pump (not shown).

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