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Cryogenic thermal studies on terminations for helium gas cooled superconducting cables

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Abstract

Details of the design of terminations for testing a superconducting DC monopole cable cooled with gaseous helium are presented. The termination design includes a liquid nitrogen chamber to reduce heat influx into the helium section through current leads. Thermal studies on the assembly of the two terminations and a 1 m or 30 m cable cryostat were performed at variable mass flow rates of helium gas. Measurements of temperature profile for the test system without the superconducting cable showed temperature rise between 5 K and 20 K depending on the mass flow rate. The temperature profile across the test system was used to estimate the heat load from different components of the system. Results with and without the liquid nitrogen in current lead section were compared to estimate the savings provided by the liquid nitrogen on the head of the helium circulation system. Suggestions for improving the design to enable fully gas cooled terminations are presented.

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Keywords: High temperature superconductor cable; helium gas cooling;termination; thermal model

1. Introduction

Power cables made of high temperature superconductors (HTS) have been of interest since the availability of the materials in long length tapes, investigated by Sinha et al. (2001), Maguire et al. (2011), and Honjo et al. (2011). Many prototype demonstrations of HTS power cables have been successfully completed and several such

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demonstrations are underway throughout the world. The majority of the demonstrations were AC power cables cooled with liquid nitrogen. Recently, the Electric Power Research Institute published a study by Eckroad (2009) on the advantages and feasibility of long distance superconducting direct current (DC) power transmission cables. One of the attractions of DC transmission systems is their suitability for smart grid concepts where power can easily be transmitted from large scale renewable energy sources such as wind farms, photovoltaic farms, and ocean wave power generators as well as interconnections between independently controlled power grids and long distance power transmission. Another advantage of superconducting DC transmission and distribution systems is the absence of AC losses in the cables that add to the cryogenic cooling capacity required to operate the cables. There have been a few demonstration projects of superconducting DC power cables cooled with liquid nitrogen. More recently, there have been projects exploring the possibility of using cryogenic helium gas circulation for cooling HTS power cables, studied by Pamidi et al. (2012) and Cheadle et al. (2013). The primary advantage of helium compared to liquid nitrogen is the possibility of lower operating temperatures that will allow the cable designs take advantage of the significantly higher critical currents of HTS tapes making the cables smaller in size and weight. Reduced size and weight are particularly attractive for naval and aviation applications as discussed by Fitzpatrick et al. (2007), Kephart et al. (2011), Ferrara et al. (2011), and Haugan et al. (2008). The United States Navy, the National Aeronautics and Space Administration, and the Air Force Research Laboratory have been investigating all-electric ships and all-electric airplanes based on superconducting cables, motors, and generators as described by Haugan et al. (2008). Lower operating temperatures are also essential for cables based on MgB_2 superconductors whose superconducting transition temperature is around 39 K and atypical cable operating temperatures are between 10 K and 20 K, studied by Cheadle et al. (2013). Circulation of gaseous or liquid neon and hydrogen are potential alternatives, but for cost and safety reasons, gaseous helium circulation has been the choice for many ongoing superconducting cable projects such as those by Fitzpatrick et al. (2007), Kephart et al. (2011), and Ferrara et al. (2011).

Superconducting DC cables do not generate any heat and hence the choice of the cryogen is not critical for thermal aspects of just the cable. Superconducting degaussing cables cooled with gaseous helium circulation have successfully been demonstrated by Fitzpatrick et al. (2007) and Kephart et al. (2011). A power transmission or distribution cable system consists of the terminations that transfer several kiloamperes of current from the network at ambient temperature to the superconducting cable at cryogenic temperatures. The heat from the ambient through the current leads and the termination tanks along with the Joule heating at the resistive joints between the current leads and the copper terminals of the superconducting cable is significant. This heat load at the terminations is one of the most challenging design aspects of helium gas cooled superconducting cables. Another design challenge for helium gas cooled superconducting cables is the substantially lower dielectric strength of helium gas, published by Rodrigo et al. (2012), Graber et al. (2011), and Rodrigo et al. (2013). The challenge is exasperated at the terminations because the warmer interfaces reduce the gas density making the dielectric strength weaker, studied by Rodrigo et al. (2013). Innovative design concepts have to be developed to address both the thermal and dielectric challenges associated with helium gas cooled superconducting cables.

The Center for Advanced Power Systems at Florida State University has been working on the design, fabrication and testing of a HTS power cable system for naval applications, published by Pamidi et al. (2012), Rodrigo et al. (2012), Graber et al. (2011), and Rodrigo et al. (2013). To provide the cooling for the cable, a cryogenic helium circulation system based on four Gifford McMahon cryocoolers and circulation fans has been built and tested. Details of the helium circulation system were previously published by Pamidi et al. (2012). To enable testing of a superconducting DC monopole cable, terminations were designed and fabricated. The designed terminations are expected to serve as part of a test bed for superconducting cables and are based on a hybrid design that includes a liquid nitrogen upper section. This paper describes the design aspects that address the thermal and dielectric issues of the terminations for helium gas cooled superconducting DC cables. The primary focus of the paper is the studies conducted to assess the heat load from the terminations and the cryostat assembly.

2. Design of the cable terminations

The superconducting DC monopole cable test system consists of the 30 m long cable in a flexible cryostat that connects to a termination unit on each end. The terminations serve as locations for injecting the current into the