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On conduction-cooling of a high-temperature superconducting cable

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Abstract

Current generation high-temperature superconducting (HTS) power transmission cables use liquid nitrogen as a coolant that circulates along the cable. In this work, the use of axial conduction-cooling in attaining HTS temperatures in transmission lines is proposed. Liquid coolant use is envisioned only at periodic length intervals along the transmission lines, in combination with insulation and copper. The proposed concept is feasible due to the high thermal conductivity of pure copper at cryogenic temperatures. A basic design for the insulated cable is proposed and a detailed numerical simulation of heat transfer in such a cable is carried out for various case studies considering the superconducting materials MgB_2 and BSCCO-2223.

Keywords: Superconducting cables (A); High T_c superconductors (A); Copper (A); Heat transfer (C); Thermal conductivity (C)

1. Introduction

Several materials conduct electricity with zero resistance below a certain temperature, called critical temperature (T_c). Some examples of such superconducting materials are: $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$, also called BSCCO-2223 ($T_c = 110$ K), $YBa_2Cu_3O_7$ ($T_c = 90$ K) and MgB_2 ($T_c = 39$ K), [1]. Low cost cooling of superconducting devices below the transition temperature is an important goal for researchers who work in the field of energy applications in cryogenics. Power transmission lines made of low-temperature superconducting material are typically cooled, by convection, through circulation of liquid helium along the cable, [2–4]. The emergence of high-temperature superconducting (HTS) material makes possible the use of liquid nitrogen as a coolant in transmission lines, thus reducing the operating cost of refrigeration [5–9]. Since in addition, HTS material has the advantage of high power density and zero environmental impact, power transmission lines using HTS cables are among the most promising applications of high-T_c superconductors. Several industrial and residential projects have now been carried out on power transmission cables cooled by convection with liquid nitrogen [10–15] and on equipment cooled by conduction [15–23].

In this work, the use of axial conduction-cooling in attaining HTS temperatures in transmission lines is proposed. The use of liquid coolant is envisioned at periodic length intervals along the transmission lines, in combination with insulation and copper, but no axial flow of liquid helium or nitrogen as coolant. The proposed concept is feasible due to the high thermal conductivity of pure copper at cryogenic temperatures [24,25]. A basic design for such a conduction-cooled high-temperature superconducting power transmission cable is proposed and a detailed numerical simulation of heat transfer in such a cable is carried out using the partial differential equation solving software FEMLAB® version 2.3.

The remainder of the paper is organized as follows: in Section 2 the proposed superconducting cable design is described. The data used for the thermal conductivity of materials are presented in Section 3. The governing set of partial differential equations that describe the temperature profile in the cable is developed in Section 4. In Section 5, the method for the numerical solution of the aforementioned differential equations is introduced. Results for

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several case studies are presented and discussed in Section 6, and conclusions are drawn in Section 7.

2. Description of the system

Two schematics of a conduction-cooled high-temperature superconducting power transmission cable segment are presented in Figs. 1 and 2. It consists of a HTS wire that is surrounded by a layer of thermal insulator, a layer of copper and another layer of thermal insulator. The insulated wire segment is represented by a cylinder with radius R and length L. The HTS material is represented by the solid cylinder with radius r_1. The copper layer is represented by the hollow cylinder with internal radius r_2 and external radius r_3 (in white, see Fig. 2). The two remaining hollow cylinders, filled with gray color, separated by the copper layer, represent the two layers of thermal insulator. The cable ends are kept at low temperature (T_0) through the use of cryogenic refrigeration systems using liquid helium ($T_0 = 4.2$ K), liquid hydrogen ($T_0 = 20.3$ K) or liquid nitrogen ($T_0 = 77.4$ K) while the ambient temperature is 300 K. The copper layer channels axially, towards the cable's cold ends, the heat that enters the cable radially through the outer insulation layer, instead of allowing it to move in the radial direction towards the cold superconductor.

In conventional convection-cooled superconducting cables, electrical current is carried by layers of HTS tapes wound helically around a flexible tube through which liquid nitrogen is pumped for cooling. The conduction-cooled cable does not employ liquid nitrogen flow along the cable, but a similar configuration of the HTS tapes, constrained to maximum external radius r_1, can be used in its design. In this case, the cylinder with radius r_1 shown in Fig. 2 contains a support tube and two concentric HTS conductors (the outer one being the return, with external radius r_1) separated by a cryogenic dielectric layer, as typically done with the so-called cold-dielectric design of superconducting cables [12]. To simplify the heat transfer analysis presented in this work, the thermal conductivity of the solid cylinder with radius r_1 is approximated to the thermal conductivity of the superconducting material.

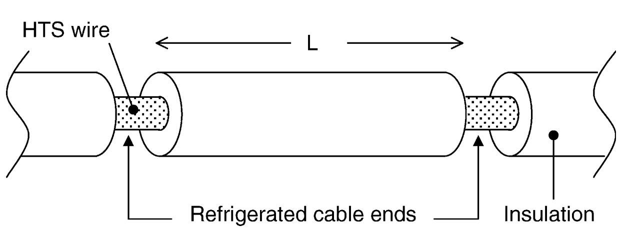

Fig. 1. Schematic of end-point refrigerated superconducting cable.

Operation of the cable under direct current (dc) is assumed here, and electrical losses are neglected in the heat transfer model presented in Section 4, because they are relatively small. In fact, Chowdhuri et al. [26] investigated the magnitude of the harmonic currents generated by power conversion at either end of a dc superconducting cable and estimated their related ac losses; for a 3-GW 100-km system, they found ripple losses below 0.0035 W/m (worst case, at 200 kV dc), much less than the thermal heat in-leak to the cryostat (3–5 W/m). They also determined ac losses to be negligible for a 500-MW 500-m system, due to the significantly small harmonic currents found in such system.

3. Thermal conductivity of materials

3.1. Copper

Eq. (1) gives the thermal conductivity k_c (W/m K) for an average sample of oxygen-free copper, as a function of temperature, T (K), [24].

$$\log k_c = \frac{2.2154 - 0.88068 \cdot T^{0.5} + 0.29505 \cdot T - 0.048310 \cdot T^{1.5} + 0.003207 \cdot T^2}{1 - 0.47461 \cdot T^{0.5} + 0.13871 \cdot T - 0.020430 \cdot T^{1.5} + 0.001281 \cdot T^2} \tag{1}$$

The thermal conductivity for this material can vary widely depending upon the residual resistivity ratio, RRR. The values calculated with Eq. (1), and plotted in Fig. 3, are similar to those obtained using the model given by Simon et al. [25] for RRR = 100. It can be noted from Fig. 3, that the thermal conductivity of copper at cryogenic temperatures reaches high values (over 2000 W/m K).

3.2. Thermal insulator

A multilayer insulation is considered. It consists of alternating layers of a highly reflecting material, such as

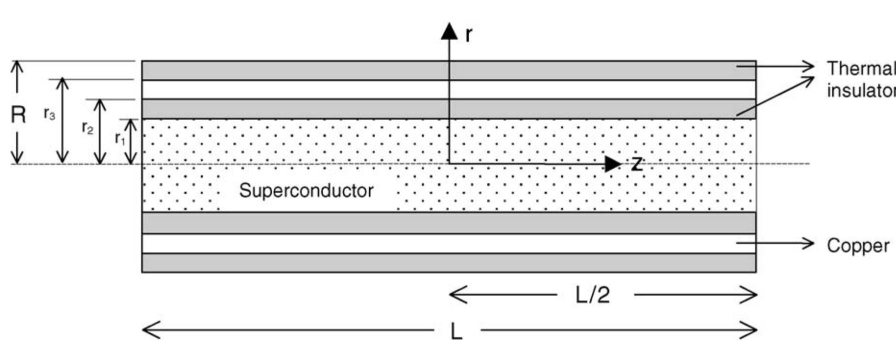

Fig. 2. Schematic of superconducting cable segment.