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Dependence of DC HTS cable critical current on the temperature distribution along the cable

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Abstract

A temperature of the long HTS cable increases with the temperature of the liquid nitrogen flowing along the cable accumulating the heat load. Therefore, the critical current decreases along the cable and in the part of the cable near outlet becomes the minimum. The critical current of the long HTS cable is estimated by the voltage drop across the cable. The typical n-value of the voltage-current characteristic of the cable is about 10-20. The decreasing of the critical current near the outlet leads the increasing of local electrical losses and it causes consequently the increasing of the local temperature of liquid nitrogen. In spite of the fact, that average electrical field is enough low ($E_0 = 10^{-6}\ V/cm$) the local current can be higher than the critical one. Measurement of the critical current with criterion of average electrical field cannot provide the safe heat losses value in every part of the cable. In the present paper the local heat generation along the cable and the method for providing the safe local DC heat losses in the every part of the cable are discussed.

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Keywords: Superconducting DC cable; heat losses; critical current

1. Introduction

A DC HTS power cable is the promising high current application for the power transmission. AC losses are absent in the DC cable and the heat load arises from the ambient heat absorption and the Joule losses when the superconductor is in the resistive state at the current near critical. The cooling down of the cable is performed by the liquid nitrogen (LN2) pumping through the long cable cryostat. LN2 is under pressure and the heat losses increase the temperature of LN2 according to the heat capacity $C_{\mathrm{LN2}} = 2\ \frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}$ (Chapter 6 of [1].

The LN2 tempe*rature and the cable temperature are different along the cable. In the inlet the temperatures are lower than the temperatures in the outlet. For the Ishikari project [2] the natural difference is about 1-3 K.

The critical current density is highly sensitive on the temperature and the heat losses increase in the area where the temperature is higher. For the long cable the Joule losses per 1 meter of length in the hot area are higher than average Joule losses fixed by the

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criterion of critical current detecting (usually electrical field $E = 10^{-6}$ V/cm).

The last experiment on the 500 m cable in Ishikari demonstrated the increasing of the temperature of LN2 at the outlet up to 1 K in case of the zero transport current. For the longer cable, the ambient heat losses will be higher and the temperature difference also will be larger. The heat resulting from the Joule losses increases the temperature of the long length cable more and the Joule losses in the LN2 outlet end of the cable is maximal.

2. The method of calculation

Fig. 1 shows the cross section of the inner part of the cryostat with the HTS cable. The size of the cryostat for analysis is taken like in the Ishikari project [2] and the CASER project [3]. The pressure of LN2 inside cryostat is about 2-3 bar. The temperature of evaporation of LN2 under this pressure is about 83-87 K [4] and the temperature of input LN2 is about 70-77 K.

For the calculation the ambient heat losses are taken into account. The values of initial temperature of LN2, T_{inlet}, and final temperature, T_{outlet}, are given as initial conditions. These values can be found more easily by direct measurement. The difference $\Delta T_{ambient} = T_{outlet} - T_{inlet}$ in the calculation is prescribed to be 1, 5, and 10 K.

The efficiency of cooling down the cable with Joule losses is proportional to the LN2 pumping rate. Pumping rate for the calculation is assumed to be 30 l/min. According to the geometry of the cable shown in the Fig. 1, the velocity of the liquid nitrogen flowing along the cryostat is $v_{LN2} = 0.35$ m/sec.

For calculation of the Joule losses in the HTS cable let's split the cable for *N* parts of equal size with index *i* = 1..*N* and with length $l_i = \frac{L_{cable}}{N}$. Let's trace the portion of LN2 flowing through the cross section S_{cable} along the cable from the inlet to the outlet. The volume of each portion is $V_{LN2} = \frac{L_{cable} \cdot S_{cable}}{N}$. When this portion of LN2 comes into the next segment of the cable the temperature of this segment increases from two sources. One is the ambient heat losses. The temperature of LN2 in every segment increases by the same value $\Delta T_{i\,ambient} = (T_{outlet} - T_{inlet})/N$. The other is the Joule heat losses. The power of Joule heat losses per unit length is current multiply by electrical field of *i*-th segment, $P_i = I \cdot E_i$. Current is the same along the cable. It is the transport current *I* maintaining by the current source. The electrical field E_i depends on the local critical current of the cable $I_c(T_i)$ which depends on the local temperature of *i*-th segment T_i. The voltage-current dependence of i-th segment is power dependence with power index *n* as follows

$$E_i = E_0 \cdot \left(\frac{I}{I_c(T_i)}\right)^n, \tag{1}$$

where $E_0 = 10^{-6}$ V/cm is electrical field criterion of critical current.

The critical current of the cable $I_c(T_i)$ vs. temperature T_i was calculated from known dependence of the critical current density taken from [5] and given amount of superconducting tapes (35 tapes) with known specified critical current of 190 A under 77 K. The dependence of critical current of the cable vs. temperature in the range 70-80 K is shown in the Fig. 2.

The Joule heat acts on the portion of LN2 near *i*-th segment of the cable during time $t_i = {}^{l_i}/_{v_{LN2}}$. The increasing of the temperature of the portion of LN2 is $\Delta T_{i\,Joule} = \frac{P_i \cdot t_i}{C_{LN2} \cdot \rho_{LN2} \cdot V_{LN2}}$, where $\rho_{LN2} = 800\,\mathrm{kg/m^3}$ is the density of LN2. After time t_i this portion of LN2 will be near next segment of the cable. Than we can write the temperature of the next segment of the cable if we know the temperature of previous segment as

$$T_{i+1} = T_i + \Delta T_{i\,ambient} + \Delta T_{i\,Joule}. \tag{2}$$

Now, it is possible to calculate the temperature of all segments of the cable because we know the initial temperature T_{inlet} of LN2. The sequential calculation with (2) gives the temperature distribution along the cable. The example of this dependence is shown in Fig. 3. Voltage at the ends of the cable is the result of summation of E_i from expressions (1) multiplied on the length of each segment l_i. The example of this dependence is shown on Fig. 4.

The value of *N* (the number of segments) is 50. This is enough to provide the accuracy of calculation about 0.1%.

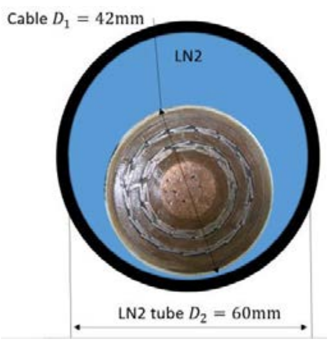

Fig. 1. Cross section of the inner part of the cable. The diameter of the cable is 42 mm, the diameter of the area with liquid nitrogen is 60 mm.

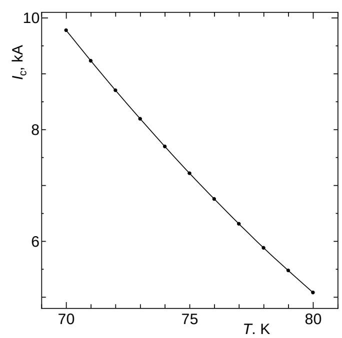

Fig. 2. The dependence of critical current of the cable made of 35 tapes of Bi2223. This dependence was recalculated from the experimental data from [5].