Temperature Distribution and Critical Current of Long HTS Cables Cooled with Subcooled Liquid Nitrogen

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Abstract. Cooling of the long HTS power transmission lines performs by pumping of subcooled liquid nitrogen (LN²) along the cable. The temperature of LN² along the cable increases due to the heat losses of the cryostat and heat generation in the HTS cable. The experiment using test cable line in Ishikari shows that flow rate of 35 L/min retains increasing of LN² temperature by 1 K per 1 km of length. The technology when the back flow of LN² cools the radiation shield surrounding the cable pipe is also applied in Ishikari-2 project. In this case the ambient heat flow into cable pipe is 50 times less than that without radiation shield. Back flow of LN² removes almost all heat coming from the environment. When transport current is close to the critical value the Joule heat of HTS cable is significant. This heat additionally increases the temperature of LN² flowing along the HTS cable. Near the outlet the temperature of HTS cable is maximal and the local critical current is minimal. The current matching critical current criterion of average electrical field of $E_0 = 10^{-4}$ V/m provides the voltage drop and significant Joule heat at the hot end of the cable. It can lead the damage of the cable. The present work contains analysis of temperature distribution along the cable and the way to achieve the fail-safe operation of long HTS cable cooled by subcooled LN². We also performed extrapolation of obtained results for several times longer cable lines by decreasing the LN² flow rate.

1. Introduction
In recent years, the large progress achieved in the field of power transmission using HTS cables. In Chubu University study of the DC HTS cables starts more than 10 years ago. First, it was 20 m HTS DC cable [1]. Next project was 200 m cable installed in 2008 (CASER project) [2]. The continuation of this work is the 500 m HTS DC cable between solar panel plant and data center in Ishikari [3, 4]. The last project is the design of 1000 m HTS DC loop cable in Ishikari [3, 4].

The present paper describes 1 km Ishikari-2 cable from Joule heat losses point of view. The cable contains two straight parts with length of 469 m and 373 m, and U-turn part with length of 125 m. The parts have different structure and different heat properties and give possibility to study the behavior of long cable system for energy transmission. The measurements of critical current of long HTS cable line is not easy because the temperature along the cable varies. The hot part of the cable is dangerous place for burning the cable because the almost all Joule heat generates in the hot place. Our previous paper devoted to the critical current of the long HTS DC cable theoretically discusses 500 m cable [5]. The present paper is the application of these ideas to the 1 km cable in Ishikari-2 project using real experimental data on heat losses in the system. The investigation of heat properties of cable longer than
existing now was performed by simulation of 5 L/min LN2 flow rate. This will be future experiment in Ishikari-2 cable.

2. Initial data and results of calculation
The calculations based on the experimental data obtained from the Ishikari-2 project. The cable has 3 sections with length of $L_1 = 469$ m, $L_2 = 125$ m, $L_3 = 373$ m. The structure of sections is shown in Fig. 1. Section 1 made with radiation shield cooled with return LN2 pipe [4]. The heat leak into cable pipe of the Section 1 is minimal. Section 2 is in U-turn area. The section are 2 and 3 without radiation shield. Two joints installed between sections. The joints have own heat leak and temperature of LN2 before and after joints is different.

![Figure 1](image1.png)

**Figure 1.** The cross-section of Ishikari-2 cryogenic pipe [4]. (a) Part of line with radiation shield connected to the pipe with return LN2 flow. (b) Part of line without radiation shield.

The result of temperature measurements at 35.17 L/min LN2 flow rate is shown in Fig. 2.

![Figure 2](image2.png)

**Figure 2.** The temperature distribution along the 1 km Ishikari-2 cable line with LN2 flows and without transport current. LN2 starts from section 3 and the temperature increases along the line. In the last part of cable (Section 1) with radiation shield temperature does not increase.

It is possible to see that liquid nitrogen starts from terminal of section 3 with temperature of $T_4 = 69.388$ K comes to joint B with temperature of $T_5 = 69.785$ K. The temperature drop of $\Delta T_{45} = 0.397$ K corresponds to heat leak

$$P_3 = \Delta T_{45} \cdot \rho \cdot F \cdot C_p = \frac{0.397}{808 \text{ kg/m}^3 \cdot \text{35.17 liters/min}} \cdot 35.17 \text{ 10}^{-3} \text{m}^3 \cdot 1.97 \text{ 10}^{-3} \text{J/kg.K} = 370.4 \text{ W}$$

for section 3. It is $\frac{P_3}{L_3} = \frac{370.4 \text{ W}}{373 \text{ m}} = 0.993 \text{ W/m}$ of ambient heat inleak in section 3.
The ambient heat leak into section 2 is $P_2 = 1.15 \frac{W}{m}$. It is close to the same value of section 3. The situation is different for section 1. The radiation shield prevents heat leak into the cable pipe of the section 1, and the temperature does not change along the section 1.

The important thing is the critical current of the HTS cable. The temperature dependence of HTS tape critical current shown in Fig. 3 was used to estimate critical current of the cable in whole.

![Figure 3](image3.jpg)

**Figure 3.** Temperature dependence of relative critical current of the Bi2223 HTS tape used in the Ishikari project.

The local temperature of the cable determines the local critical current. Fig. 4 illustrates the dependence of temperature, voltage (now it is 0 because transport current is 0), and local critical current of the cable on the position.

![Figure 4](image4.jpg)

**Figure 4.** The dependence of temperature (a), voltage (b), and local critical current (c) on the position. The LN2 flow rate is 35.17 L/min and transport current is 0 A.

The obtained heat leak data allow to calculate the influence of flow rate on temperature distribution. The decreasing of flow rate can simulate the system operation when the HTS cable length becomes longer. Fig. 5 shows the same dependences as in Fig. 4 but at the LN2 flow rate of 5 L/min.
The transport current flowing in the HTS cable heats up the cable. The Joule losses are not homogeneously distributed along the cable. The voltage drop depends on the value of transport current and the proximity of transport current to the critical current according the voltage-current characteristic. Paper [5] describes the method of calculation of voltage drop in the long cable with LN2 flow and transport current. This method includes the splitting of the cable on small parts with size $x_i$ and local temperature $T_i$. Local critical current $I_c(T_i)$ is obtained using data from Fig. 3, and then we can calculate electrical field in this element $E_i$:

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

where $E_0 = 10^{-4}$ V/m – criterion of critical current.

The $n$-value of the cable was 10 – 20. The length of the cable in the paper [5] was 500 m. In our case the length is 1000 m and step of calculation is $x_i = 1$ m. The value of transport current takes to obtain the total voltage on the cable corresponding to the criterion of average critical current with average electrical field $E_0 = 10^{-4}$ V/m. Total voltage of the cable is

$$U = \sum_{i=1}^{N} E_i \cdot x_i = U_0 = E_0 \cdot N = 0.1 \text{ V}.$$

The result of calculation for 1 km line with ambient heat inleak shown in the Fig. 6d. It is possible to see that the maximal local Joule heat is about 1.5 times larger than average ($E_0 = 10^{-4}$ V/m). It means that hot end of the cable is overloaded by 1.5 times in terms of heat generation.

The situation with LN2 flow rate of 5 L/min is different. The value of electrical field at the end becomes much higher than $E_0 = 10^{-4}$ V/m. Fig. 7 shows the same dependence like in Fig. 6 but for LN2 flow of 5 L/min.

**Figure 5.** The dependence of temperature (a), voltage (b), and local critical current (c) on the position. The LN2 flow rate is 5 L/min and transport current is 0 A.

**Figure 6.** The dependence of temperature (a), local critical current (b), voltage (c) and local electrical field $dU/dx$ (d) on the position in case of LN2 flow rate of 35 L/min and transport current of 4795 A (n=15), 4792 A (n=20), 4789 A (n=25) to obtain the total voltage drop 0.1V.
Figure 7. The dependence of temperature (a), local critical current (b), voltage (c) and local electrical field \(\frac{dU}{dx}\) (d) on the position in case of LN2 flow rate of 5 L/min and transport current of 3847 A (n=15), 3840 A (n=20), 3837 A (n=25) to obtain the total voltage drop of 0.1 V.

From Fig. 7d it is possible to see that the electrical field at the hot end of the cable is more than 10 times higher than average electrical field. It means that the Joule heat, which is electrical field multiply by current \(P = I \cdot E\) is also 10 times higher at the hot end. The transportation of current with value equals to the critical current obtained with criterion \(10^{-4}\) V/m is dangerous for the cable.

The measurement of critical current is better to perform by pulse current with duration about 2 sec. This estimation comes from the average heat capacity of HTS tape material (mainly stainless steel) and resistivity of the tape at low temperature [6]. The increasing of the temperature in this case even the cable comes to the normal state will be less than 200 K.

In order to estimate the safe value of maximal nominal current the same characteristics were calculated in case of 90% value of the measured critical current. The temperature, critical current, voltage and electrical field distributions along the length are shown in the Fig. 8.

Figure 8. The dependence of temperature (a), local critical current (b), voltage (c) and local electrical field \(\frac{dU}{dx}\) (d) on the position in case of LN2 flow rate of 5 L/min and transport current of 3837 A (n=25) to obtain the total voltage drop of 0.1 V.

The value of transport current for different LN2 rates was also calculated. The result is shown in Fig. 9. It can be seen the dependence on LN2 flow rate, but not on n-value. The reason is the temperature of hot end is different for different LN2 flow rates. The critical current of the cable decreases for the case of low LN2 flow because the temperature of the hot end of HTS cable becomes higher than in case of high LN2 flow rate.
Figure 9. The dependence of critical current of 1 km Ishikari-2 type cable line for different LN2 flow rates for different n-values.

3. Conclusion

The present research deals with calculations of heat processes in 1 km cable using experimental data from Ishikari-2 project. It is important for the experiments critical current measurement of HTS cable in Ishikari-2.

The estimation of critical current is only possible by measurement of voltage across the cable. However, the voltage according the criterion of $10^{-4}$ V/m is dangerous from cable thermal stability point of view because of the nonuniform temperature distribution along the cable. The hot end of the cable will be overloaded in spite of the average voltage across the cable is enough low. To solve this problem the measurements can be performed supplying with current pulses and critical current can be detected with criterion of $10^{-4}$ V/m and the further account that the transport current should not be more than value 10% less than the value of measures transport current. It makes the safe exploitation of the cable.

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