Cooling Cycle Test of DC Superconducting Power Transmission Cable

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Abstract. We constructed a test stand of a 20 m DC superconducting power transmission cable in Chubu University in 2006. The cable uses thirty-nine Bi-2223 tapes. Four cycles of a cooling and current-feeding test have been carried out after the construction of the test stand. The cable suffered rapid temperature decrease of 20 K/hour at the daytime during the cooling process by cold nitrogen gas and liquid to the liquid nitrogen temperature. Nineteen HTS tapes in the cable are electrically isolated from each other, and the superconducting characteristics of these HTS tapes can be measured separately. At every cooling cycle, critical current of these isolated HTS tapes were measured. Consequently, no reduction of the critical current characteristics was observed through the 4 cooling cycles. We considered that this endurance of the cable against the cooling cycle is due to unfixed cable end structure of the cable, and that the cable was free from the mechanical stress in spite of the 6 cm shrinkage of the cable length under the low temperature.

1. Introduction

One of the difficulties to realize the superconducting power transmission (SC-PT) was the energy to cool down such a large scale system to very low temperature. However, due to the development of high temperature superconductors (HTS), the SC-PT system can use liquid nitrogen (LN2) as coolant, which makes the SC-PT system using HTS practical. Recently, several practical projects of the AC SC-PT system have started or been planned in the world[1]-[7].

Meanwhile, the AC SC-PT systems have the inevitable problem of the AC losses of HTS tape conductors. The DC SC-PT system is free from the AC losses, and the operating current of the DC SC-PT cable can be larger than that of the AC SC-PT cable. Therefore, Hassenzahl et al. started assessing a high power DC SC-PT system of multi-gigawatt with very long distance[8]. One of the serious problems of the DC SC-PT is that the DC SC-PT system needs expensive AC/DC converters with high voltage and high current capacity. Yamaguchi et al., have proposed a DC SC-PT system
with a relative low transmission voltage less than 30 kV to use commercial AC/DC converters of several kilovolts[9].

We constructed a DC SC-PT cable test stand in 2006 to study the high current and low voltage transmission, and started the first experiment in October 2006[9]. In the past articles [9][10], we reported electric properties of the DC SC-PT cable and the reduction of heat leakage by installation of the Peltier current lead. In this article, we will describe the test stand during the cooling-down process and the influence of the 4 cooling cycles on the HTS tapes in the cable.

2. Experimental device

We started to construct a test stand of DC SC-PT cable in April 2006, and completed in October 2006[9]. Figure 1 shows the layout of the DC SC-PT cable test stand in Chubu University. Total length of the DC SC-PT cable was about 20 m. The DC SC-PT cable was cooled by the circulation of sub-cooled liquid nitrogen. The LN2 circulation system in figure 1 consisted of a LN2 reservoir, a LN2 pump, and two G-M cryocoolers, as shown in table 1. We have carried out the 4 periods of the cooling tests for this system since the test stand was constructed, as shown in Table 2.

Figure 2 shows a cut-model of the DC SC-PT cable manufactured by Sumitomo Electric Industry Ltd. Designed specification of the cable was 3 kA current feed and 20 kV insulation at 78 K. The conductor of the cable was composed of two layers of Bi-2223 HTS tapes; 19 tapes were used in the inside layer and 20 tapes were used in the outside layer. Note that the HTS shield layer is not necessary for a DC SC-PT cable. Initial critical current and n-value of the HTS tapes were 107 A and 20, respectively. One of the characteristics of our DC SC-PT cable is that the HTS tapes in the inside layer does not touch each other. Hence, the properties of every HTS tape in the inside layer can be individually examined after cooling down the cable[10]. A copper(Cu) former and a Cu shield in figure 2 were connected to the earth potential at the cable end of the cryostat A in figure 1.

![Figure 1. Layout of a test stand of 20 m DC superconducting power transmission(SC-PT) cable.](image)

| Table1. Specification of LN2 circulation system | Table2. Periods of cooling test. |
|-----------------------------------------------|---------------------------------|
| **Equipment** | **Specifications** | **Number** | **Period** |
| G-M Cryocooler | 2 sets | 1st period | Oct.--Dec. 2006 |
| LN2 pump | Cooling power: 220 W/1 set at 80 K, 60 Hz | 2nd period | Jun.--Aug. 2007 |
| | 1 set | 3rd period | May--Aug. 2008 |
| | Flow rate: 7~12 L/min | 4th period | May--Jul. 2009 |
On the test stand, the cable was installed in thermally-insulated double-pipes (cryopipe) made of smooth stainless steel to reduce the system cost, the radiation heat [11], and pressure drop of cryogen [12][13] for smooth pipes. Total length of the cryopipe was about 16 m. Figure 3 shows the cross-section of the cryopipe. Supporters of FRP were placed at the 8 points in the cryopipe to keep the space between the inner and the outer pipes. Superinsulation was wound on the inner pipe as a heat radiation shield. When the 20 m cable and the 16 m inner pipe are cooled by LN2, they shrink by 0.3% after cooling down. Bellows were inserted in the cryopipe to absorb the shrinkage of the cable and the inner pipe, as shown in figure 1. In addition, the cable ends were not fixed to the cryostat to be free from the mechanical stress on the cable due to the cycles of cooling-down and warming-up.

We employed three kinds of monitoring methods during the cooling-down processes. First one was the Pt-Co resistive thermometers located on the wall of the cryostats (A and B in figure 1) and the cryopipe (position A, B, and U in figure 1). Heights of the thermometers were center of the cryostats and the cryopipe. Second one was voltage of the one HTS tape in the inside layer at 10 mA. The last one was the displacement of the length of the bellows A and B inserted in the outer cryopipe.

3. Experimental results

3.1. Cooling-down process

In the cooling-down processes, coolant was provided from the cryostat A, through the cryopipe, to the cryostat B only at daytime, for 6 ~ 8 hours a day. Targeted cooling speed of the cryostat A was 20 K/hour; coolant was cold N2 gas at first, and then was changed to LN2. Figure 4 and 5 show the time dependence of the data of the three monitors during the cooling-down processes of the 3rd and the 4th period, respectively. In both cases, 4 days were necessary to achieve superconductivity of the HTS tapes and to finish the cooling-down process.

In figures 4(b) and 5(b), HTS resistance was normalized by the data before cooling down. In both the 3rd and the 4th processes, HTS resistance steeply increased at the night of the 3rd day (2008/5/19~20 and 2009/5/18~19). This means that a part of the HTS tape reached superconducting in the cooling-down of the 3rd day, and then its superconductivity was lost with increasing temperature during the night.

Displacement of bellows length (figure 4(c) and 5(c)) followed the temperature of cryopipe, and the total displacement of the bellows A and B reached 38.9 mm at the 3rd cycle and 38.0 mm at the 4th cycle. Consequently, these bellows absorbed about 80% of shrink of the inner pipe.

At the 4th period, another temperature monitor was tested. Electric resistance of the 20 m Cu former decreases following the temperature in the cooling-down process; therefore, the temperature of the Cu former can be estimated from the temperature dependence of electric resistivity of Cu. The temperature dependence in [14] was used for this estimation. Figure 5 shows the time dependence of Cu former temperature estimated from that of the electric resistance of Cu former. Since the
temperature difference between cryostat A and B in figure 4 (a) could cause the large temperature difference between both ends of the 20 m Cu former, the electric resistance measurement were carried out with eliminating the Seebeck voltage due to this temperature difference. Compared with figure 5(a), time dependence of the Cu former temperature was similar to that of the cryopipe U; the temperature estimated from the electric resistance of the Cu former represented the mean temperature of the cryopipe.

![Graph](image1)

**Figure 4.** Time dependence of (a) cryostat and cryopipe temperatures, (b) HTS resistance normalized at room temperature, and (c) displacements of bellows, during the 3rd cooling-down process.

![Graph](image2)

**Figure 5.** Time dependence of (a) cryostat and cryopipe temperatures, (b) HTS tape resistance normalized at room temperature, and (c) displacements of bellows, during the 4th cooling-down process.

![Graph](image3)

**Figure 6.** Time dependence of temperature estimated from the electric resistance of Cu former during the 4th cooling-down process.
3.2. Effect of cooling cycles
One of the advantages of our DC SC-PT cable is that we can measure the properties of the 19 HTS tapes in the inner layer individually, since they are electrically isolated to each other. Therefore, the critical current and the $n$-value of each HTS tape in the inner layer were measured at every cooling cycle. At the 3rd period, the critical current measurement was carried out at various temperatures from 74.1 K to 79.7 K, and it was found that the critical current at the 1st and the 2nd period fit well to the temperature dependence at the 3rd period[10]. Also at the 4th period, the critical current of each HTS tape was measured at 76.5 K, and the mean value of the critical current at the 4th period fit well to the same line as shown in figure 7(a). The mean $n$-value was 19–21 and independent to the temperature and the cooling cycle, as shown in figure 7(b).

Consequently, there were no damages on the HTS tapes throughout these 4 cooling cycles, in spite of the steep cooling-down speed as shown in figure 4 and 5. We concluded from these results that (1) the bellows inserted in the cryopipe and (2) the structure at the unfixed cable ends effectively absorbed the mechanical stress on the SC-PT cable due to the 4 cycles of cooling-down and warming-up.

4. Conclusion
We constructed a test stand of a DC superconducting power transmission cable in October 2006 in Chubu University, Japan. Afterwards, 4 periods of cooling test was carried out. No damage on the critical current of HTS tapes measured during these periods whereas the cooling speed was 20 K/hour. Consequently, our system can absorb the mechanical stress due to the shrinkage of the cable, and can prevent the damage on the HTS tapes.

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