Research activities of DC Superconducting Power Transmission Line in Chubu University

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Abstract. A experiment of a DC Superconducting power transmission line using HTS conductor was started in Chubu University, Japan in autumn 2006. The first cooling down began in October 2006. The coolant is liquid nitrogen, and the cooling system used a cryogenic cooler and cold pump. The operation temperature is the range of 72 K – 80 K. The power cable has a total length of 20 m, and composed of thirty-nine Bi-2223 HTS tape conductors with critical current approximately 100 A. The power cable achieved a 2.2 kA. The insulation voltage of the cable is 20 kV. In order to reduce the heat leakage and to avoid the current imbalance in the HTS tapes, we installed the Peletair Current Lead (PCL) for each of the nineteen HTS tapes of the cable, with remaining twenty HTS tapes connected individually by the usual copper leads (CCL). Depending on the visual observation, and the measurement of temperatures of the current leads, the heat leakage of the PCL is lower than that of CCL. We installed a current transformer for each individual HTS tape conductor circuit, and measured the current of each HTS tape conductor. We measured the critical current of each HTS tape after the cable was installed into the cryostat, and degradation was not observed. Since the variation of the current in each tape is less than 10%, we eliminated the problem of current imbalance. Computational Fluid Dynamics is used to estimate the pressure drop, showing that the straight-tube cryostat has the advantage against the bellows- and corrugated-tube cryostats to reduce the pressure drop of the circulation of coolant. We proposed further to use the siphon for circulating the coolant in order to reduce the circulation losses and costs. We proposed that the voltage of the system be kept below 30 kV in order to use low cost power inverters. This choice can increase the storage energy of the power transmission line itself if we do not use a co-axial cable system because of it allows use of large current. And the magnetic energy of power grid is estimated to 4.5MJ/km for ±30 kA.

Introduction
The many applications of the high temperature superconductor (HTS) had been developed for various fields, and one of the major fields is the power transmission line. Several projects were focused to
develop the AC power cable [1]-[3] for past 10 years. One of the key issues of the ac applications is to reduce the AC losses of the HTS tape conductor [4]-[8], and if the AC losses will be reduced enough to the practical level, the ac application will have large markets. However, the superconducting system has lots of benefits in the DC applications. Because of much effort to develop the superconducting technology in the past 20 years, the engineering problems of the power cable are understood clearly, and the HTS tape conductors can be available for the DC applications in the present technology. And it is not necessary to concern that the many engineering problems originated from the AC losses. But if we are going to develop the DC power transmission line, we must consider the cost of the inverter because the cost of inverter is very expensive in the DC power transmission line for the copper cable system because an ultra-high voltage must be used to reduce the losses, and this is a real reason why the development of the power cable was started for the AC applications past 15 years ago. However, the DC power transmission line has been used even for the copper cable system from the last 50 years in all over the world [9]-[11]. Actually the efficiency of the DC system is higher for a long distance power transmission line, and effective even for short distance if the cable is installed into the water. Moreover, the DC system is lower investment cost, has a high controllability and a function of asynchronous interconnections, limits the short circuit current, and is good for environment [9]-[11]. These merits are realized and enhanced for the copper cable system in the present time, and these are the ultra-high voltage system (UHV, 250kV to 800kV). But even for the short-distance, relative low voltage (2 kV to 4 kV) and copper cable system, the DC power transmission line is thought to be effective by the recent development of the inverter [12]. This consideration is matched well for DC superconducting power transmission because we do not need to use UHV for superconducting system. Because of these reasons, the DC superconducting transmission line was started to research [13].

We describe the project of the DC superconducting power transmission line (DCSC-PT) in Chubu University as an international collaboration. The experiment of the project was started in autumn 2006, and the critical current of the HTS tape conductor of the cable and its current distribution are reported in this paper. The first experimental result of the Peltier current lead (PCL) for the SC cable are also presented. Finally, we discuss how to choose the parameters of voltage and current for the DCSC-PT and the magnetic energy storage effect of the superconducting cable system.

1. Experimental Device
We started to construct the experimental device of the DCSC-PT in Spring 2006, and completed in Autumn 2006 Chubu University, Japan. The first cooling down was started in October, 2006. The total length of the SC cable is 20 m, and the SC cable is shown in figure 1.
Figure 1. This is a photo of a DC superconducting power cable installed into the experimental device, in which 39 HTS tapes are used for two layers, and the insulation voltage is 20 kVDC, made by Sumitomo.

The Bi-2223 HTS tape conductor [14] is used, and its critical current is slightly larger than 100 A at temperature of 77 K, and the number of the tape is 39 for two layers. We do not use the magnetic shield layer like an AC superconducting power cable in order to reduce total AC losses of the cable. These tapes are connected to the strands of the current lead individually and the copper power cable is connected with each current lead terminal as shown in figure 2. The current transformer (CT) to measure the current is installed into each copper cable, therefore we can measure the current of individual HTS tape independently when the HTS tapes are insulated each other. We installed the PCL [15] configuration into the cryostat at the each end of the cable as is shown in figure 2. The material of Peltier part is bismuth-telluride alloy (BiTe). The objective of the PCL is to reduce the heat leakage from the current lead to improve the efficiency of the system. This is important when we construct the short DCSC-PT because the major heat leakage comes from the current lead.

Figure 2. Configuration of the cryostat for current lead and its connections for power supply.
We also adopt the straight inner pipe and a larger pipe diameter as compared with the diameter of the SC cable for minimize the pressure drop of the cryogen circulation, and the aspect ratio of the inner and outer pipe radius is higher than that of the previous researches for the AC power cable in order to reduce the heat leakage by the radiation. In order to absorb the thermal expansion, the short bellows pipe is connected to the straight pipe, and the thermal expansion is estimated to be 6 cm for the total length of 20 m. The end support of the SC cable is set to be free for the direction of the thermal expansion and the other two directions are fixed. Therefore, the tension of the SC cable would be almost zero in all range of the temperature.

1.1. Measurement of critical current of HTS tape conductor
After the SC cable was installed into the cryostat and connected to the current lead, we measured the electric properties of the system. Since the CT is connected to each HTS tape circuit and the voltage taps are also connected to the HTS tape, we can measure the critical current of each HTS tape if it is insulated each other. The inner layer of the SC cable is composed of nineteen HTS tapes, and fortunately they are insulated each other in spite of any insulation of the HTS tape surface even after the installation of the cable. Figure 3 shows the first result of the relation of voltage and current for the HTS tape of 11th.

![Figure 3](image.png)

Figure 3. The horizontal axis is the normalized current, and the magnitude of 120 A is unity. The vertical axis is electric field and its unit is µV/cm.

If we assume the definition of the critical current of 1.0 µV/cm, the critical current of the HTS tape is 105.1 A, and the index number is 14.6. We will measure the critical current of each HTS tape after the cryogenic cycle will be done, and it is important to watch the change of the characteristics of the HTS tape. Each HTS tape of the outer layer is touched with each other, therefore we could not do the critical current measurement of each HTS tape for the outer layer of the SC cable like figure 3.

1.2. Measurement of current distribution of inner HTS tape conductor
Since the each HTS tape is not connected with each other in superconducting state for the outer layer of the SC cable, we can measure the current of each HTS tape independently. This is important to watch the current imbalance [16] of the HTS tape conductor to maximize the performance of the SC cable. Unfortunately, since the one of HTS tapes was not connected to the current lead terminal, we
had no data of this HTS tape, however we could measure the currents of the other nineteen HTS tapes. Figure 4 shows the currents for the outer HTS tapes, and the temperatures of the current leads. Two thermocouples (TC) are connected to each one current lead and one TC is connected near the room temperature side and the second TC is connected near the current feeder of the liquid nitrogen (LN2) vessel. The temperatures of the cold side varied by the operation time, but they are several degree. Total current is 1.2 kA and the variations of the current and temperature is not large, and therefore the current imbalance problem can be solved in this system.

![Figure 4](image)

*Figure 4.* Currents of the HTS tape conductors in outer layer of the SC cable, and temperatures of the current leads. Two thermocouple are connected near the room temperature side and the cold side for one current lead.

1.3. Pelteir current lead (PCL) experiment

The PCL is installed for the inner layer of nineteen HTS tapes as is shown in figure 2. The Peltier material is bismuth-telluride alloy (BiTe alloy), and the p-type material is connected to the negative electrode of the electric power supply and the n-type material is connected to the positive electrode for expectation as the heat pump when the current pass through the Pelteir materials. The thermal conductivity of BiTe alloy is almost 0.3 % of the copper’s, therefore the thermal resistance of the current lead is increased and we can expect the reduction of the heat leakage even for the current of zero. The conventional current lead (CCL) is also installed for the outer layer of the twenty HTS tapes, and it is composed of only the copper cable. Figure 5 shows the photo of the current lead terminals at the room temperature side both for PCL and CCL. The difference between PCL and CCL is clear, and the terminal of the CCL is frozen and the terminal of PCL is not frozen. This is the direct proof that PCL can reduce the heat leakage from the current lead. The thickness of the BiTe alloy is 8 mm, but the temperature difference of the BiTe alloy exceeds 100 K for the current of 30 A. We analyze the data of the temperature and will report the details of the PCL experiment soon.
2. Discussion and Future Research
The maximum current of 2.2 kA was achieved in the first cycle of the experiment. The important research is to fix the parameters of the voltage and current for the DCSC-PT. It is not necessary to use UHV system because the resistance of the DCSC-PT is very low. Therefore, we proposed to use several to 30 kV for DCSC-PT. The reasons are Corona free system. Corona is one of the high voltage discharge in atmospheric pressure in air, and if we are free from the Corona, all instruments of the system are easy to make, and it is effective to reduce the cost, especially for inverters. Recently the technology of the power electronics is advanced, and we should take into account of the progress of the power electronics, and fix the parameters for the total system. Finally, we can expect high efficiency, too. If we can use relatively lower voltage system, the magnitude of the current should be large because of sending the same electric power.
Since the transmission line has the inductance, the DCSC-PT itself can store the magnetic energy like the SMES [17]. The magnetic energy of the power grid is around 4.5 MJ/km for the current of ±30 kA. This value is not small as compare with the present SMES. The SMES effect is matched well to send the electric power from the renewable energy source like solar panel and wind firms basically because we can control the output power and get the stability of the power transmission. This research also relates with the power electrics, and it must be studied to reduce the emission of green house gases in the earth.
The other research field to realize the DCSC-PT is related with the fluid dynamics. The liquid nitrogen must be circulated inside the long pipe cryostat, and we should take into account of the pressure drop of the circulation. In order to reduce the pressure drop of the circulation, one of the effective ways is to use the straight tube instead of using bellow and/or corrugate tube. Depending on the numerical calculation of the fluid dynamics, the pressure drop is 10 times difference at least. If we use the slash nitrogen, we must consider the multiphase flow of nitrogen, such as solid and liquid, and liquid and gas. We also propose to use the siphon principle to circulate the fluid. The cooling station should be placed higher place, and the cold and heavy nitrogen is sent into the pipe, then the heavy nitrogen falls down to lower and lighter nitrogen will lift up. This idea can reduce the circulation power, and therefore we can reduce heat load to the cryo-cooler and do not necessary to develop a high output pressure pump for the circulation. We did the calculation of the idea analytically, and it will be reported soon. These are future research subjects.
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