Study of Bulk Current Leads for an Axial Type of HTS Propulsion Motor

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Abstract. The high-temperature superconductor (HTS) bulk current lead (BCL) is a significant device for a large number of current applications into the propulsion motors with HTS windings. The coexistence of low thermal conductivity and superconductivity enables us to shrink the dimension of the power transmission system. For the effective usage of the BCL, one has to optimize the dimension and the temperature gradient across the BCL length. We have made the BCL with a melt growth bulk crystal of GdBa₂Cu₃O₇₋ₓ by ourselves, serving for the introduction of the excitation current to the coreless Bi₂223 superconductor winding field-pole magnets applied to the axial-gap type motor. We successfully installed the BCL and obtained a thermal gradient of 40 K across the BCL with 75 mm length under the current flow of 200 A, necessary to operate the superconductor windings at 30 K below \( T_c \). The use of the BCL enabled us to suppress the thermal transfer into the coil vital part down to 6 W from the external power source. The present result shows that BCLs effectively operate while being connected to superconductor coils in propulsion motors.

1. Introduction

The theory of using bulk current lead (BCL) has been studied for the industrial applications with windings of high-temperature superconductor (HTS) tape [1,2]. For those applications, the electric power causes problems in the direct transmission from the power supply at the room temperature to the HTS magnet cooled at low temperature. Conventional copper electrical leads have been primarily used due to their high electrical conductivity and mechanical expediency. The high conductivity, however, causes an inevitable thermal conduction as well which increases the low-temperature heat load and needs excessive cooling power to suppress the heat. Extension of the copper lead length is one of the solutions to avoid the heat invasion. Although, this brings an increase of the system volume, as well as Joule heat from the extended part of copper lead.

The melt-growth crystal of HTS has been applied to the current leads. They are significant applications to reduce the heat described above, because they successfully combine both carrying a large amount of charge together with low heat thanks to their poor thermal conductivity below \( T_c \). Therefore, the materials and mechanical design of the BCL have been studied and applied to large-current superconducting applications [3,4]. In our previous work, we studied BCL and succeeded to
fabricate 300-A class BCLs of melt-growth bulk crystals of GdBa$_2$Cu$_3$O$_{7-z}$ (Gd123) [5]. We have focused on HTS motors for electric ship propulsion. Thanks to the significant potential of HTS, the rotating machines have been fabricated and tested all over the world [6-8]. We have undergone an intense study of an axial-gap type HTS motor, used for relatively small power propulsion [9]. Also, we carried out to apply HTS windings to the larger motor, whose application will be found in larger vessels and other MW-class applications [10, 11]. Compared to the bulk HTS, the HTS windings are convenient to increase the magnetic flux as a function of the applied DC current. In this respect, we have designed and assembled a propulsion motor with Bi2223 wire windings.

In this paper, we report that the BCL has been successfully optimized and assembled to the HTS axial-gap type synchronous motor.

2. Experimental

2.1. Structure of the bulk current lead (BCL)

The specifications of the BCL are listed in table 1. We fabricated the BCLs with a melt-growth of Gd123 bulk HTS (QMG, Nippon Steel Co. Ltd.,: GdBa$_2$Cu$_3$O$_{6.9}$ 70.9 wt. %, Gd$_2$BaCuO$_{5.0}$ 19.2 wt. %, Pt 0.5 wt. %, Ag 9.4 wt. % in composition, 10 mm in length, 20 mm in width and 2 mm in thickness), which has low thermal conductivity below $T_c$ [12].

A photograph and design parameters of the BCLs are shown in figure 1. We optimized the dimensions of BCLs for an axial-gap type coreless synchronous motor. The size of a BCL is 75 mm in length and 20 mm in width. In order to strengthen the stability from external forces, both electrodes are connected through GFRP, which has lower thermal conductivity and shrinkage in the cryogenic condition. Both bulk and copper electrode surfaces are jointed in association with a metal alloy impregnation. The optimum temperature range for high- and low-temperature ends of the BCL are 60 - 80 K and 30 - 40 K, respectively [5].

![Figure 1. Bulk-current lead (BCL) of Gd123 fabricated by using the metal impregnation.](image)

| Operating Current at T(K) | 300 A @ 90 K |
|---------------------------|--------------|
| Material                  | Gd123 Bulk   |
| Length                    | 75 mm        |
| Cooling                   | Conduction cooling |
| High temperature end      | 60 K- 80 K   |
| Low temperature end       | 30 K- 40 K   |
2.2. Specifications of HTS motor

A photograph of the HTS motor with Bi2223 winding coils and its peripheral equipments are shown in figure 2. As shown in table 2, we have successfully studied both design and assembly of a prototype of an HTS axial-gap type synchronous motor for a power propulsion use [10].

Figure 3 shows a schematic inner structure of the Bi2223 HTS field poles. The rotor is composed of a shaft and of a torque tube, together with current leads for HTS field-pole coils, as well as the necessary thermocouples and cryogenic parts for the circulation of the refrigerant on the same axle. Thermal and electric characteristics of these coils were sufficiently studied in the previous work [13]. Coils are excited by a DC power supply through collector slip rings and BCLs. Field-pole windings are cooled down by conduction cooling through the rotor plate, thanks to a refrigerant in the cooling chamber located inside the motor shaft. The bulk current lead is also cooled down below 60K, which is lower than the $T_c$ of a Gd123 bulk.

The HTS field poles were excited by a DC power source, from the outside of the motor through the brush and the collector slip rings. To protect the field poles from the heat radiation of the armature, we cooled down the armature coils to around 80 K with liquid nitrogen flowing from a cooling path separated from the field-poles’. In the motor frame made of non-magnetic SUS, vacuum is acting as thermal and electric shields to insulate the rotor. The mechanical stability of the rotor is maintained by using a couple of mechanical bearings and magnetic fluid seals.

![Figure 2. An axial type of HTS propulsion motor with Bi2223 field poles.](image)

**Table 2.** Features of an axial-gap type HTS motor with Bi2223

| Motor type       | Axial type, synchronous motor |
|------------------|-------------------------------|
| Coil type        | 8 split-type field poles       |
|                  | composed of 16 coreless DPCs   |
| Superconductor   | Bi2223 wire                   |
| Diameter         | 850 mm                        |
| Length           | 507 mm                        |
| Output           | 100 kW                        |
| Rating           | 230 rpm                       |
| Weight           | 1044 kg                       |
3. Cooling and Operation test of the Gd123 BCL

3.1. Cooling test
The cooling test of the BCLs mounted in our Bi2223 HTS motor was carried out with successive coolings. It took 780 minutes after the start to cool down below 30 K the temperature of the field poles, which is the working temperature of the rotor poles during motor operation.

Figure 4 (a) shows the temperatures at the high- and low-temperature ends of the BCL in the motor. The BCL is successively cooled down. Practically, the bulk HTS lead has to be cooled down below the critical temperature of Gd123 and under the suitable thermal gradient for the current to be efficiently applied to the field poles. The resulting temperatures of the bulk HTS lead at the high- and low-temperature ends were actually 69 K and 36 K by using a single-stage GM refrigerator. The presently developed temperature regulation for the BCL has enabled to apply a large operating current up to 300 A without any heat leak from the field poles to the external electrodes.

Figure 4 (b) shows the temperature of a HTS field-pole coil as a function of time upon successive coolings by using both liquid nitrogen and gas helium. The straight line indicates the target temperature of the field pole, which is 30 K. It was found that the whole HTS field pole was cooled down to 20 K within 780 minutes.

The lead connection from the external electrode to the high-temperature end of the bulk current lead successfully suppresses the heat transfer down to 13 W. Furthermore, the use of the bulk HTS current lead enabled us to decrease the total thermal transfer below 6 W. This residual heat transfer value is sufficiently small to allow the HTS windings to be cooled down until low temperatures in the motor.

3.2. Excitation of the HTS coil with a DC current flow through the BCLs
Figure 5 (a) shows the temperature variations of both high- and low-temperature ends of the BCLs as a function of the applied DC current flow. Applied current rating was 5 A/min in the whole experiment. Curves indicated as $T_h$ and $T_l$ indicate the measured temperatures at the high- and low-temperature ends of the bulk BCL, respectively. After the application of the field-pole current of 200 A, the high-temperature end increased by only 3 K from 69 K and the low-temperature end remained stable around 40 K.
In addition, the temperatures of the HTS windings have not been changed much under the 200 A applied current, as shown in Figure 5 (b). It was found that the present BCL satisfactorily provides temperature stability at 30 K even when a current of up to 200 A is applied to the Bi2223 field-pole magnets in the HTS motor.

**Figure 4.** Temperatures upon cooling by liquid nitrogen and subsequent cooling with gas helium at high-temperature ($T_H$) and low-temperature ($T_L$) ends of the BCL (a) and the temperature on the top of the HTS field-pole winding of Bi2223 (b).

**Figure 5.** Temperatures as a function of the applied DC current flowing into the field poles at high-temperature ($T_H$) and low-temperature ($T_L$) ends of the BCL (a) and the top of the HTS field-pole winding (b).
4. Summary
We have studied BCLs using Gd123 bulk HTS with different dimensions. The prototype design was optimized to 75 mm in length for the HTS motor with Bi2223 windings, which is aimed to be employed as a propulsion motor. Thanks to the compact dimensions of the present BCL, we successfully assembled them in the small space of the torque tube. In the present study, by using liquid nitrogen and helium gas, both ends of BCL and HTS windings were successfully cooled down below $T_c$. By considering thermal conduction and invasion, BCL provides a thermal gradient of 40 K across high-temperature and low-temperature ends. The pole-field Bi2223 winding was successfully maintained below 30 K, which is operation temperature of the Bi2223 wire, when we applied the excitation current up to 200 A to the HTS coil through the BCLs. The presently developed Gd123-BCLs successfully kept the thermal gradient under the applied current condition and showed a significant stability for HTS rotating machines as motor and/or generators.

5. References
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