Abstract

Efforts on the generation of intensified magnetic flux have been made for the optimized shape of HTS winding applications. This contributes to the high efficiency of the rotating machines using HTS windings. Heat generation from the HTS windings requires to be suppressed as much as possible, when those coils are under operation with either direct or alternative currents. Presently, the reduction of such thermal loss generated by the applied currents on the HTS coils is reported with a magnetic flux deflection system. The HTS coils are fixed together with flattened magnetic materials to realize a kind of redirection of the flux pathway. Eventually, the magnetic flux density perpendicular to the tape surface (equivalent to the a-b plane) of the HTS tape materials is reduced to the proximity of the HTS coil. To verify the new geometry of the surroundings of the HTS coils with magnetic materials, a comparative study of the DC coil voltage was done for different applied currents in prototype field-pole coils of a ship propulsion motor.

Keywords: Bi2223 tape; Heat generation; HTS rotating machine; HTS winding

1. Introduction

Large-scale industrial machines with high-temperature superconductors (HTS) have been targeted for decades [1 - 4]. For the application to ship propulsion, the HTS motors with different output powers have been tested by several research groups and companies [5, 6]. We have developed a 1 MW-class radial-
type motor with HTS windings for ship propulsion [7]. In this respect, the cryomechanical and structural designs as well as the field poles’ construction have been completed in a HTS rotating machine [8]. For the HTS winding, Bi2223 tape has been employed thanks to practical availability with its performance in the present stage [9, 10]. It is known that an applied magnetic field perpendicular to the HTS tape drastically decreases the critical current compared to a parallel field. In our previous study, the field-angle dependence of the critical current density in the Bi2223 HTS tape surface was studied intensively with prototype windings [11]. According to the results, we have calculated the electric power loss of the HTS winding under practical motor operation conditions.

Recently, a technique of magnetic flux deflection (MFD) was applied to the design of HTS poles. The magnetic flux vector was successfully controlled with the magnetic plates to reduce the Joule heat and maximize the effective flux reaching the armature windings. An examination was conducted with two kinds of Bi2223 HTS double-pancake coils (DPCs).

2. Experiment

Fig. 1 shows the photographs of DPCs submitted to the present study. They are a single race-track-shaped DPC and a conventional DPC in which five DPCs have been stacked, as respectively shown as a) and b) in Fig. 1. The specification details of the coils are summarized in Table 1.

The schematic views of the experimental configurations are shown in Fig. 2. Liquid nitrogen is used for cooling and keeping the temperature of the HTS coil at 77 K during the measurements. DC current was applied with a power source (Takasago Ltd., FX035-344) to excite these coils, until it reached the critical current of each winding. The critical current of the coil was adopted following the $1 \, \mu V/cm$ criterion, with the coil voltage divided by the length of the Bi2223 tapes used in the winding. To observe the magnetic flux density generated from the coil, Hall sensors were assembled on and beside the coils, as shown in Fig 2. Sensor 1 and sensor 2 measure the magnetic field parallel to the Bi2223 tape surface $B_{\parallel}$, which is equivalent to the vertical direction for the top plate of the coil. The field perpendicular to the tape surface $B_{\perp}$ was measured by sensor 3, set at the outer surface of the winding, as exhibited in Fig. 2 (a).

Fig. 2 indicates the setup location of the MFD for each coil. They were attached on both top and bottom plates of a set of HTS coils. In the present experiment, SS400 mild steel was selected thanks to the advantage of a high saturated flux and low cost. Sizes of the inner and outer diameters were determined following the dimension of the HTS winding. The MFD for coil A and coil B were 3-mm thick and 9-mm thick, respectively.

![Fig. 1. Photograph of prototype coils (a) Coil A : Single DPC coil (b) Coil B : Stacked DPC coil](image-url)
### Table 1. Parameters of double pancake test coils

<table>
<thead>
<tr>
<th>Coil ID</th>
<th>Coil A: Single DPC coil</th>
<th>Coil B: Stacked DPC coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_c$ @ 77 K, self field</td>
<td>150 A class</td>
<td>80 A class</td>
</tr>
<tr>
<td>HTS conductor</td>
<td>Sumitomo Bi2223</td>
<td>Sumitomo Bi2223</td>
</tr>
<tr>
<td>Number of turns</td>
<td>400 turns</td>
<td>1550 turns</td>
</tr>
<tr>
<td>Inner and Outer diameters</td>
<td>ID: 66 mm, OD: 184 mm</td>
<td>ID: 60 mm, OD: 161 mm</td>
</tr>
<tr>
<td>Total length of HTS tape</td>
<td>240 m</td>
<td>10500 m</td>
</tr>
</tbody>
</table>

![Fig. 2. (a) Schematic view of the experimental system. (b) Position of the Hall sensors. The sensor 1 is located 3 mm above coil center and measures the magnetic field flux density $B_{\parallel}$ parallel to the Bi2223 tape plane (a-b axes plane). The sensor 2 is located among the HTS winding on the top plate of the MFD, which measures $B_{\parallel}$ component. The sensor 3 at the contour of HTS winding measures the magnetic field flux density $B_{\perp}$ which is perpendicular to the Bi2223 tape plane.]

#### 3. Results and discussions

In order to study the effect of MFD on the critical current and heat generation, excitation test in self field was employed. Fig. 3 shows the resulting curves of the applied current vs. the induced DC voltage measured across the current lead terminals of the coils shown in Fig. 2. Voltage drop per unit length [$\mu$V/cm] was calculated from the terminal voltage and wire length. By adopting the MFD, the critical current of the coil A was enhanced from 55.8 A to 57.8 A, according to the $1 \mu$V/cm criterion. In the coil B, the critical current of the coil was enhanced from the ordinary critical current of 23.6 A to 30.7 A.

Fig. 4 shows the magnetic flux density as a function of the applied current. Magnetic field increases with increasing the currents for the DPC coils. In the case of Coil A, $B_{\parallel}$ measured by Sensor 1 and Sensor 2 at the critical current were increased by 12.8 % and 46.0 %, respectively. In addition, Sensor 3 observed a suppression of $B_{\perp}$ of 4 % at critical current in the results without MFD. In the case of Coil B, magnetic flux densities at Sensor 1 and Sensor 2 under application of the critical current were enhanced by 23.2 % and 9.6 %, respectively. Under the critical current measured without MFD, the observed $B_{\perp}$ at the sensor 3 was decreased by 13.3 % in the case the MFD was used.

Heat generation of the coils with and without MFD was calculated based on the results of the $I$-$V$ curve. Both of them are compared for applied currents around the critical current observed in the case without MFD. For the coil A, heat generations under the applied current of 55 A were 0.63 W and 1.17 W in the cases of with and without MFD, respectively. For the Coil B, the values with and without MFD were 0.13 W and 0.85 W under an applied current of 23 A. The reduction of the heat losses were 46.4 % and 85.1 % for Coil A and Coil B, respectively.

According to the results of Coil A and Coil B, it is concluded that the coil to which the MFD is attached has better performances, i.e., sees a lowering of its thermal and electric losses. The reduction of
heat generation has been clarified thanks to the suppression of the perpendicular magnetic flux density in both coil A and coil B. It was achieved more effectively in Coil B than in Coil A. Several reasons have been advanced, considering the difference in specifications between Coil A and Coil B, such as the number of stacked DPCs, the thickness of the MFD materials and the base performance of the HTS tape used for the winding. The MFD is more efficient for a stacked coil, because the perpendicular field, $B_{\perp}$, becomes significantly large by increasing the number of the stacked coils. This advantage of the MFD may be examined in future rotating machines applications and the geometry of the MFD must be optimized to increase the efficiency under the optimization of electric, thermal and cryomechanical designs.

4. Summary

Properties of superconducting coils with and without MFD were successfully verified. $I-V$ curves of a single race-track DPC and a stacked round DPC were obtained by flowing from 0 A to their critical currents in the coils. The heat generation of the Bi2223 coil with MFD is remarkably lower than without MFD, over a wide range of applied currents. As well, the enhancement of critical current of the coils was observed. These results are coming from the contribution of MFD with reducing the perpendicular magnetic field component applied to the Bi2223 tape. The reduction of heat generation using MFD is a feasible approach. This technique is not only effective for industrial motors, but also for other practical applications using HTS as high-field magnets.

![Fig. 3. $I-V$ curve and heat generation as a function of applied current with and without MFD (a) Coil A (b) Coil B](image)

![Fig. 4. Magnetic field as a function of applied current (a) Coil A (b) Coil B](image)
Acknowledgments

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References