Study of field-pole Bi2223 windings of air core type for a HTS propulsion motor

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Abstract. In the present study, we designed a field pole of Bi2223 superconductor winding without iron core applied to high-temperature superconducting (HTS) motor of an axial gap type. As the preliminary step to form a field pole winding, we designed a double-pancake-coil (DPC) and qualified relationship between the terminal voltage and the excitation current. We adopted the structure of HTS winding field pole composed of stacked two layered DPC because of effective conduction cooling and electromagnetic effect. We manufactured 16 poles DPC and verified the critical current vs. terminal voltage at 77 K with liquid nitrogen. To form a rotor, 8 field-pole HTS windings were manufactured by integrating of two DPCs as a split coil. We measured the coil \( I_c \) and voltage drop of the terminal at 30 K cooled with gas-liquid mixing helium and qualified the heat generation from the coils with DC current excitation. The cooling and excitation test of the constructed field pole coils were performed in the testing motor. The results exhibit that presently developed coils possesses sufficient performance on the heat generation and the magnetic flux density in the axial-type machine under construction.

1. Introduction

In the last half decade, high temperature superconducting (HTS) motor for all electric ships has been attracted in all over the world. Several HTS testing motors of radial gap type have been fabricated. In the previous work, we have studied a HTS motor of an axial gap type for use of relatively small power propulsion, in which the HTS bulk magnets were applied as a multiple pole-field on the rotor and the copper armature coils were without iron core. This bulk HTS motor has been a trial to be built up a compact and light weight propulsion motor without increasing mass coming from iron. From these experiences, it has become clear that a core-less electromagnetic structures may realize both compact and light weight as a HTS motor which is similar to the idea proposed in USA. With the elemental techniques about conduction cooling etc. from this primarily works, we have tried to develop a propulsion motor of axial gap type with HTS winding. A field-pole HTS coil with high magnetic flux density provides a high torque. The motor has to be light weight and small size without iron core. This is a reason why we need to develop a high performance field-pole coil without iron core. Recent research indicates that YBCO called as the second generation HTS wire has been developed. The critical temperature \( T_c \) of YBCO is above 90 K, critical current \( I_c \) of it is also higher than high temperature superconductor developed ever. Therefore, it looks like easily found that YBCO HTS...
wire has a good performance about magnetic flux density. YBCO wire, however, is presently necessary for a production cost and isn’t mass-produced HTS wire. On this account, we decided to employ a Bi$_2$Sr$_2$Ba$_2$Cu$_3$O$_{10}$ (Bi2223) HTS wire with high cost-effectiveness. Bi2223 wire has been established to manufacture firmly in Japan and US. Bi2223 wire has considerably good performance for generation of magnetic flux density, and it is used by many HTS rotating machines so far. We try to produce high-performance HTS field-pole winding using high quality Bi2223 wire applying to HTS propulsion motor.

At the first step of manufacturing HTS winding, we designed double-pancake-coil (DPC); it is called because of looking like a stacked two pancakes; and produced it using Bi2223 HTS tape. To be stacked up these DPC, HTS windings were manufactured. They produced field-pole coils and we estimated on the relationship between $I_c$ and the voltage of terminals together with magnetic flux density. Additionally we mounted these windings on the axial rotor of the testing motor of 100 kW 230 rpm and conducted excitation test.

In this paper, we give the results on these qualifications about Bi223 based pole field windings.

2. The shape and the manufacturing method of two layered DPC type filed-pole

We manufactured 16 DPCs with 160 mm in diameter using Bi2223 HTS wire and excited these coils by DC current at liquid nitrogen temperature (77 K). Then, we measured the value of critical current of the coil. The voltage was measured by four-terminal method. Figure 1 shows relationship between the voltage of terminals and the applied current. Table 1 shows the critical current ($I_c$) of DPCs and Table 2 shows the critical current of field-pole winding made by stacking of the DPCs. From table 1, we compared with each critical current of DPC, and found the difference of the critical current of the coil was 6.8 A at maximum. The structure of field-pole winding unit was adopted two-layered DPC; the cooling plate was sandwiched between DPCs according to the cryogenic design of cooling efficiency and its electrical design. To reduce difference of $I_c$ of field-pole winding units, we made it by combining DPCs of highest $I_c$ and lowest one among the DPC coils, eventually we manufactured 8 HTS windings field poles from 16 DPCs with stacking two by two. The picture of HTS field-pole winding developed in this research is shown in figure 2. The voltage of terminals was measured at copper electrode shown in the top of figure 2. From table 2, it could be found the difference of $I_c$ of field-pole windings was able to keep below 2 A. We accomplished manufacturing HTS windings with little differential of performance.

The characteristic of these field-pole HTS winding is not an electromagnet with iron core type which has been used in the HTS motor with liquid nitrogen cooling. The present core-less type field-pole coils enable us to operate the magnetic field beyond the saturation flux density of iron core.

![Figure 1. I-V characteristics of a field-pole at 77 K](image-url)
Table 1. The critical current of DPCs at 77 K

| DPC # | No,d1 | No,d2 | No,d3 | No,d4 | No,d5 | No,d6 | No,d7 | No,d8 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Ic [A]| 60.5  | 58    | 58    | 60.5  | **62.5** | 59.5  | 60    | 60.8  |
| No,d9 |       |       |       |       |       |       |       |       |
| No,d10|       |       |       |       |       |       |       |       |
| No,d11|       |       |       |       |       |       |       |       |
| No,d12|       |       |       |       |       |       |       |       |
| No,d13|       |       |       |       |       |       |       |       |
| No,d14|       |       |       |       |       |       |       |       |
| No,d15|       |       |       |       |       |       |       |       |
| No,d16|       |       |       |       |       |       |       |       |

Table 2. The critical current of field-pole windings at 77 K

| Coil # | No,1 | No,2 | No,3 | No,4 | No,5 | No,6 | No,7 | No,8 |
|--------|------|------|------|------|------|------|------|------|
| Ic [A] | 45.4 | 44.2 | **46.0** | 45.5 | **44.0** | 45.8 | 45.5 | 44.0 |

Figure 2. HTS field-pole winding for the axial-type rotor in the present cryo-mechanical design

3. Experimental results on the DC current excitation at 30 K

An effective Bi2223-based HTS winding operation is necessary to cool down below at least 55-30 K by using a closed-cycle neon refrigeration associated with a GM AL330 cryocooler. The refrigerating system has a limit for cooling power as 60 W at 30 K. To cool down and keep effectively low temperature cooling of the field poles, therefore, we have to design and manufacture with a reduced heat generation as much as possible upon current loading up to e.g., 200 A.

Preliminary, the field-pole winding as previously noted was cooled down to close to 30 K by gas-liquid mixing helium, and we applied the current to the winding up to 200 A with dc current. The generated voltage between two terminals was measured with four-probe method, and we calculated heat release value and magnetic flux density by measured voltage. Table 3 shows voltage between two terminals when the dc current was applied to 200 A at 30 K. From this experimental result we calculated heat generation values and we found that the average value of calorific power for the coils was able to keep 0.24 W (gross heating value was 3.9 W). This heat value is sufficiently small, we found that these HTS winding is utilizable to cool down until low temperature in the motor.

Next, we measured magnetic flux density with Hall probe sensor. Figure 3 shows the obtained magnetic flux density at z = +6 mm above the center of the top support plate. This value of z = +6 mm means the air gap in our designed motor. From these experimental data we found that these field-pole
windings could have 1.2 T with 200 A. Thus, the presently qualified field-pole windings may lead to the realization of the compact size, light weight and high torque motor.

![Graph of magnetic field test](image)

**Figure 3.** Magnetic field-test at z = +6mm above the center of the top support plate of the winding

**Table 3.** Voltage drop of the field-pole coil excited with 200 A at 30 K

| Coil # | No,1 | No,2 | No,3 | No,4 | No,5 | No,6 | No,7 | No,8 |
|--------|------|------|------|------|------|------|------|------|
| V[mV]  | 1.16 | 0.68 | 0.78 | 1.29 | 1.25 | 1.00 | 1.09 | 0.58 |

4. Cooling test of field-pole winding in the motor

We have done a cooling and excitation test with HTS field-pole winding assembled to the rotor plate in the motor under construction. The preliminary cooling test was carried out by using liquid helium but actually we use the cooling system with a closed-cycle condensed neon system associated with a GM-type cryocooler (AL330, Cryomech Co.). The cooling system with a closed-cycle condensed neon in the motor is shown in figure 4. Neon gas injected into the cooling system is condensed with a GM cryocooler from passing near the cold head and field-pole windings are cooled by conduction cooling with thermal siphon of the condensed neon reached to center of rotor. 8 x 2 field core-less pole windings on the rotor are cooled down by a conduction cooling. Figure 5 shows the results of the cooling test of the HTS field-pole winding in the motor with liquid helium. It was found that the field-pole windings were also able to cool certainly below 55 K in the motor. The results of the excitation of the magnetic field in the motor are shown in figure 6. In the present stage, the dc current excitation up to 50 A and it was confirmed to excite the rotor field-pole windings inside the motor. The HTS motor applied to HTS field-pole windings are shown in figure 7.

From these experimental data, these field-pole windings were sufficiently acceptable in the motor.
Figure 4. Cooling system using a GM cryocooler AL330 with condensed neon. The rotor base temperature was successfully cooled down to 38 K.

![Diagram of cooling system](image)

Figure 5. Cooling test of the field-pole winding on the axial-type rotor in the motor

![Graph of temperature vs. time](image)

Figure 6. Magnetic field B(T) vs. applied current test result (B(T) was measured at z = +6 mm above center in the motor.

![Graph of magnetic field vs. current](image)
5. Summary

For the axial-type propulsion motor operating with a closed-cycle neon cooling system, the field-pole windings of Bi2223 wires without iron core was designed and the product was tested at 55 K with a dc current excitation in the motor. The constructed field-pole windings yield up more than 1.2 T at +6 mm from the top plate of the winding. The present results also issue that the designed refrigeration and the cryomechanical system is acceptable for the pole-field windings with conduction cooling on the rotor disk in the axial-type motor. The HTS coils developed in this study are expected to enables us to reduce the weight drastically because of core-less, the size of the motor and to increase the torque density. It is expected that the present coils are able to achieve high torque density of motor with 1.2 T of dc field in armature windings region. The present HTS windings coil without iron let us enhance the magnetic field flux beyond the saturation of the magnetic flux density of a conventional core. It is expected that the capability of the field-pole winding is improved spectacularly with performance advances of super conducting wire in years to come.

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