Development of a field pole of 1 MW-class HTS motor

S Yuan¹, Y Kimura¹, ², M Miki¹, B Felder¹, K Tsuzuki¹, T Ida³, M Izumi¹, K Umemoto², K Aizawa² and M Yokoyama²

¹ Department of Marine Electronics and Mechanical Engineering, Tokyo University of Marine Science and Technology, 2-1-6, Etchujima, Koto-ku, Tokyo 135-8533, Japan
² Kawasaki Heavy Industries Ltd., 1-1, Kawasaki-cho, Akashi-shi, Hyogo 673-8666, Japan
³ Department of Electronic Control Engineering, Hiroshima National College of Maritime, Toyota-gun, Hiroshima 725-0231, Japan

E-mail: m084024@kaiyodai.ac.jp

Abstract. We report a field-pole high-temperature superconductor (HTS) magnet designed for 1 MW-class motor for propulsion. The field pole is assembled to the rotor of the radial-type motor. Each field pole is composed of HTS-Bi2223 tape wound into coils which have been piled up as a double pancake coils. In the design concept of the motor, we employ field poles without iron core. We prepared the test field-pole coil, whose dimension is smaller than the designed one for 1 MW, and tested its performances after cooling under self-field and external magnetic field. We verified the operation with the minimum bend radius of the coils required in the motor design, while keeping an optimal current which is lower than the critical current of the field-pole coil. The test HTS field poles were successfully cooled down and operated under a magnetic field ranging up to 5 T. We report the results of the test field-pole coil and the manufacture of a practical racetrack coil with Bi2223 and discuss the adaptability to 1 MW-class motors.

1. Introduction

High-temperature superconductor (HTS) motors for electric propulsion have attracted a considerable interest in the world [1-3]. Several HTS testing motors of both radial- and axial-gap types have been fabricated [4,7]. In the previous study, we have studied the cryomechanical design and construction of a HTS motor of axial-gap type for use for relatively small power propulsion, in which the HTS bulk magnets of GdBa2Cu3O7-z (Gd123) were applied on the rotor as field poles (8 60-mm diameter bulks) and the copper armature coils without iron core were assembled [7]. Gd123 bulk material is one of the families of 2G tape as Y123. Pulsed-field magnetization was applied to Gd123 bulks by using the copper armature coils. We have successfully developed a propulsion motor of axial gap type with HTS windings by using Bi2223 tape [4]. The rotor poles have been successfully cooled and kept at the operating temperature thanks to a thermal-conduction cooling by using liquid nitrogen and helium. It has become clear that a core-less electromagnetic structure realizes compact and light weight as a HTS motor, an idea originally coming from the 5-MW and 36.5-MW radial-type motors developed in the USA [4,5]. In the past works and based on advanced techniques together with thermal-conduction cooling for HTS magnets, we have tried to develop a 1 MW-class radial-type motor with HTS windings for podded propulsion. Our designed model motor aims at being eventually installed in the pod of commercial ships. The pod is a mature propulsion technology as reported in Queen Mary 2 and
DAT in North Sea. Over MW class propulsion motors become heavy and large in both induction and synchronous motors. The dimensions of the pod may be reduced considerably by employing HTS motors. In this respect, a field-pole HTS coil with high magnetic flux is definitively necessary to provide a high desired torque under the optimized design. Thus the motor would be light-weight and small-sized, thus suitable for potted propulsion. The motor will be installed inside the pod with direct-drive propellers. This is a reason why we presently develop a high performance field-pole coil without iron core.

2. Design of a racetrack-type field-pole coil

At the present day, there are two species of HTS tape materials in the practical application level. One is the tape made of YBa$_2$Cu$_3$O$_{7-x}$ and the other is Bi2223 tape, whose superconducting transition temperatures $T_c$ are 93 K and 110 K, respectively. According to $T_c$, the application at liquid nitrogen boiling temperature has been proposed. However, commercial specifications for both types of tapes are insufficient for proper windings without iron core (or air core) to be applied as field-pole magnets. Some types of HTS motors were proposed by using iron cores in the centre of the windings [8]. In the concept of core-less field-pole coils, the magnetic flux density has to be large to obtain high flux around the surface of the poles.

On this account, we have adopted a Bi2223 HTS tape at the operating temperature of 30 K. The specification of the Bi2223 tape is an $I_c = 155$ A at 77 K under self field. On that tape, table 1 shows the example results of the voltage drop under different excitation dc currents and applied external magnetic fields B. The direction of B is perpendicular to the surface of the tape. The manufacture of Bi2223 tape is now firmly established in Japan, the USA and other countries. Bi tape as well as 2G tape, in the present status, has to be used below 40 K to 50 K to prevent heat loss.

| Magnetic field | V(μV/cm) @100A | V(μV/cm) @150A | V(μV/cm) @200A | V(μV/cm) @250A | $I_c$(A) @40K |
|----------------|----------------|----------------|----------------|----------------|---------------|
| 0.5 T          | 0              | 0              | 0              | 0.13           | 280           |
| 1 T            | 0              | 0              | 0.2            | 1.4            | 240           |
| 1.5 T          | 0              | 0              | 0.4            | —              | 210           |
| 2 T            | 0              | 0.2            | 1.8            | —              | 180           |
| 2.5 T          | 0.5            | —              | —              | —              | 165           |
| 3 T            | 1.4            | —              | —              | —              | 145           |
| 4 T            | 0.4            | —              | —              | —              | 120           |
| 5 T            | —              | —              | —              | —              | 75            |

Table 1. The voltage drop observed at 40 K on the fragment of Bi2223 tape under different magnetic fields perpendicular to the tape surface.

At the first step of manufacturing the HTS winding, we designed a racetrack coil (RTC) (called that way because looking like a racetrack) and produced it using Bi HTS tape. HTS windings were manufactured and then piled up to make the RTC. They produced field-pole coils we estimated on the relationship between $I_c$ and the voltage, under a magnetic field ranging up to 5 T. Because the field-pole HTS coil is assembled to the rotor, it has to be used under a variety of electromagnetic fields. For example, the magnet field vector will be applied under different angles as calculated. As a result, we operated a current test of the Bi HTS tape under a magnetic field ranging up to 5 T with cooling down to 40 K. It is noted that we employ a Gifford-McMahon (GM) cryocooler to design and construct the cooling system. The cost is mostly the same for cooling down a system to either 4K or the liquid nitrogen temperature. Indeed, re-condensation systems of nitrogen or sub-cooling systems are operated with GM or equivalent He cryocoolers.

For getting the optimized assessment of the coil assembly, we have done a calculation of the magnetic field density distribution by the Magnet software [9]. The operating temperature is presumably set at 30 K, for getting at a 1 MW power the most suitable shape of coils, interval between
poles and the applied electrical current flow. Figure 1 shows the result of the designed coil assembly. The maximum magnetic field is 3.6 T as shown in figure 1 under a 150 A current flow excitation.

The characteristic of this field-pole HTS winding is an electromagnet without iron core which has been used in the HTS motor under a liquid nitrogen cooling. The present core-less type field-pole coil enables us to operate the magnetic field beyond the saturation flux of iron core.

![Shaded Plot](image)

Figure 1. Magnetic field density profile of the RTC with a 150 A current flow.

3. Test field-pole coil and its characterization under a magnetic field up to 5 T
Following the field-pole design as described in section 2, it is necessary to verify the function of the coil, especially focusing on the generation heat coming from voltage drop under both high current and high magnetic field.

We have designed a test RTC, whose length is shorter than the practical RTC’s, which has the same coil parameters, except the length of the straight portion of the coil. The coil is composed of a winding of Bi2223 tape. The adopted structure of the field-pole winding unit was a two-layered RTC forming a double pancake coil (DPC). The profile and the photograph of the test DPC are shown in table 2 and in figure 2, respectively. The \( I_c \) of the coil is 267 A at 30 K under self field. We have tested the voltage-current characteristics at 40 K under a magnetic field parallel to the length axis of the test RTC. The applied magnetic field was ranging from 0 T to 5 T.

The winding part of the DPC was sandwiched between copper plates to be cooled down by thermal conduction, since connected to the cryocooler refrigeration. The voltage drop generated from the HTS winding under the dc current excitation was measured by the four-terminal method. Figure 3 shows the schematic view of the current-voltage characteristic under a magnetic field parallel to the length axis of the test RTC. The thermocouple temperature sensors were attached on the copper plate surface and positioned as T1 and T2, as indicated in figure 4. V1 and V2 indicate the voltage drop generated from the only HTS winding and the whole DPC together with the copper electric blocks, respectively.

Figure 5 (a) and 5 (b) show the relationship between the voltage of terminals and the applied current under a magnetic field of 4 T, as well as the temperature variation with increasing the excitation current flow.

We stopped applying current to the coil at 175 A because quick voltage rise until 149 \( \mu \)V occurred. From these results, we can see that it is possible and safe to apply a 150 A current to the coil at 30 K, for getting enough power.
Table 2. The profile of the test coil (RTC).

| Specification                  | Value     |
|--------------------------------|-----------|
| Length of the tape             | 32 m      |
| Number of turns                | 30        |
| Entire length                  | 288 mm    |
| Width                          | 92 mm     |
| Length of the straight portion  | 133 mm    |
| Radius of curve                | 23.5 mm   |

Figure 2. HTS field-pole test coil for the radial-type rotor.

Figure 3. Schematic view of the experimental arrangement during the determination of the current-voltage characteristics of the test RTC under magnetic field parallel to the long axis.
Figure 4. The thermocouple temperature sensors were attached on the copper plate surface, positioned as T1 and T2. V1 and V2 indicate the voltage drop generated from the only HTS winding and the whole DPC together with the copper electric blocks, respectively.

Figure 5. (a) The relationship between the voltage drop of the HTS winding and RTC including copper electrodes, under the applied current and magnetic field of 4 T. (b) The temperature variation of the test RTC during the current flow in a 4 T magnetic field.

The same cooling and voltage-characterization study was then conducted on the test RTC under 5 T. The experimental geometry and the positions of the sensors are the same as in the study under 4 T shown in the figure 3.

Figure 6 (a) shows the relationship between the voltage of terminals and the applied current under a magnetic field of 5 T. Figure 6 (b) shows the temperature variation during the current flow.

We stopped applying current to the coil at 150 A because the voltage rapidly rose until 143 μV. From these results, we can see that it is possible to apply a dc excitation current up to 150 A to the test RTC even in a 5 T magnetic field at 30 K.
Figure 6. (a) The relationship between the voltage drop for the HTS winding and RTC including copper electrodes under the applied current and magnetic field of 5 T. (b) The temperature variation of the test RTC during the current flow in a 5 T magnetic field.

The generation heat of the test RTC was calculated with the relationship between the voltage drops V1 and V2, and the applied current in figures 5 and 6. Table 3 shows the calculation results. It is obvious that the observed temperature rise in figure 5 (b) and figure 6 (b) does not come from the HTS winding of the test RTC itself, but the reason mostly originates from the heat coming from the copper electrodes and the related elements including the joining part with the HTS winding.

| Current (A) | 4T V1 | 4T V2 | 5T V1 | 5T V2 |
|------------|-------|-------|-------|-------|
| 100 A      | 0.0001 W | 0.06 W | 0.0001 W | 0.06 W |
| 150 A      | 0.0003 W | 0.15 W | 0.0215 W | 0.15 W |

4. Operating of dc current excitation at 30 K of the designed RTC for rotor of 1MW motor

Figure 7 shows the overview of the RTC for practical application to a 1-MW motor’s rotor field pole. The coil is composed of a winding of Bi2223 tape with $I_c = 160$ A under self field at 77 K. The adopted structure of the field-pole winding unit was a two-layered RTC forming a double pancake coil (DPC). The $I_c$ of the coil is 225 A at 30 K under self field. We have tested the voltage-current characteristics at 31 K under self field. The winding part of the DPC was sandwiched between copper plates to be cooled down by thermal conduction, since connected to the cryocooler refrigeration. The voltage drop generated from the HTS winding under dc current excitation was measured by the four-terminal method. The thermocouple temperature sensors were attached on the copper plate surface positioned as shown in figure 4. The voltage drop generated from the only HTS winding and the voltage drop generated from the whole DPC together with the copper electric blocks were measured as V1 and V2, respectively. The results are shown in figure 8. The total length of the Bi2223 tape is around 2000 m. As shown in figure 8, the calculated heat generation from the only part of DPC winding of Bi2223 tape was 0.1 W under a dc excitation current of 200 A at 30 K. On the other hand, the calculated heat including remaining parts of the RTC such as copper electrodes and joining substance between Bi2223 tape and the copper blade was below 0.5 W. These values are satisfactory
and the generated voltage drop under 200 A operation at 30 K was less than 0.05 μV/cm on the whole length of the used Bi2223 tape.

Figure 7. The overview of the RTC for practical application to a 1-MW motor’s rotor field pole.

Figure 8. The voltage drop generated from the only HTS winding and the voltage drop generated from the whole DPC together with the copper electrodes were measured as V1 and V2, respectively.

5. Summary
For a 1 MW-class radial-type ship propulsion motor, a field-pole winding of Bi2223 tape without iron core was designed and the short-length test field pole was made and operated at 30 K with a dc current excitation under a magnetic field up to 5 T. The HTS coils developed in this study are expected to enable us to reduce successfully the voltage drop generated from the Bi2223 wire and its junction with copper electrodes. This achievement leads to an operation of the HTS pole field coil able to generate an intensified magnetic flux, effective for the armature. It has become clear that the generated heat from the only Bi2223 winding is much less than that from the copper joining and electrodes. Figure 7 shows the overview of the RTC for practical application to a 1-MW motor’s rotor field pole. The practical pole-field coil was composed of a winding of Bi2223 tape with \( I_c = 160 \) A under self field at 77 K. The adopted structure of the field-pole winding unit was a two-layered RTC forming a double pancake coil. The \( I_c \) of the coil is 225 A at 30 K under self field. We have tested the voltage-current characteristics at 30 K under self field. The total length of the Bi2223 tape is around 2000 m. The heat generation from the only part of DPC winding of Bi2223 tape was 0.1 W under a dc excitation current of 200 A at 30 K. On the other hand, the calculated heat including remaining parts of the RTC such as
copper electrodes and joining substance between Bi2223 tape and copper blade was below 0.5 W. These values are satisfactory and the generated voltage drop under a 200 A operation at 30 K was less than 0.05 \( \mu \text{V/cm} \) for the whole length of the used Bi2223 tape. The present HTS winding coil without iron let us enhance the magnetic field flux beyond the saturation encountered with a conventional core. It is expected that the capability of field-pole windings is spectacularly improved along with the performance advances of superconducting tape in years to come.

6. References

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