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Pulsed-field Magnetization Study for Gd123 Bulk HTS Cooled with Condensed Neon for Axial-gap Type Synchronous Motor

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Abstract. The closed-cycled refrigeration of neon by using a GM cryocooler has successfully provided a low-temperature pulsed-field magnetization at 38 K for field-pole Gd123 bulks in the testing rotating machine. Upon magnetization, a new split-type of armature coil, Controlled Magnetic field density Distribution Coil (CMDC) was employed. The CMDC has realized a control of magnetic field by choosing effective diameter of the vortex coil either 44 mm or 84 mm for the sample with 60 mm in diameter. The maximum trapped magnetic flux density reached over 1.3 T at 1.3 mm from the surface of bulk. 2.5 times larger flux was obtained for the field pole bulk in contrast to the liquid nitrogen cooling. The output of the motor was enhanced to 25 kW associated with a practical closed-cycle cooling without a liquid cryogen.

1. Introduction

A high-temperature superconducting (HTS) motor has attracted a considerable interest to reduce a mass, a dimension together with high torque density in contrast to a conventional motor. Especially, all electric ship has been configured in the marine and the ship transportation from the viewpoint of several advantages including consideration of earth environmental protection and sustainable energy saving. In this respect, the reduction of both size and mass are strongly required for the mobile function in the electric ships with pods, since the propulsion motor has to be included in the pod outside the hull. The requirements of light weight and small sized rotating machine have strongly motivated the formation of field pole and/or armature coils by using superconducting wire. In both US and Germany, they have developed a large scale synchronous machine for testing to condenser, generator and/or ship-propulsion motor application up to 36.5 MW with 230 rpm which is equivalent with 47,000 Nm/m³ as torque density [1]. On the other hand, the superconducting bulk HTS motor was implemented in several laboratories and it aims to a practical use as power conversion to propulsion [2-4]. A HTS bulk is a melt-growth superconductor by mixing several second materials with roles of stabilization and/or reinforcement of pinning force. We have conducted to develop an axial-gap type synchronous motor by using GdBa₂Cu₃O₇₋₄ (Gd123) bulk HTS field pole magnets. To activate the pole field with eight poles of bulk HTS on the rotor, a pulsed-field magnetization (PFM) was employed for
the bulk HTS with a split type armature coils cooled with liquid nitrogen [5]. The output of bulk HTS motor reached 10 kW at 720 rpm. The average trapped magnetic flux density was 0.53 T.

In the present study, we focused on an output improvement of the bulk motor. The output of the motor depends on the magnetic flux density and the armature current density as well. The trapped magnetic flux density in the field-pole bulk increases with decreasing cooling temperature of the bulk. The bulk HTS placed on the rotor disk inside the motor was successfully cooled down with a closed-cycle circulation of condensed neon inside the rotor by using a compact GM cryocooler. The magnetic flux penetration is not easy to penetrate into the bulk HTS according to the diamagnetic effect by cool down to lower temperature than liquid nitrogen cooling. In the PFM procedure, with decreasing magnetization temperature, minute by minute, the step cooling was used [6, 7]. In addition, we have developed a Controlled Magnetic density Distribution Coil (CMDC) [8] by which we can control the magnetic field by choosing effective diameter of the vortex coil either 44 mm or 84 mm, inner and/or outer coils. Eventually, trapped flux density has been improved as well as the output of the bulk HTS motor by using these combined techniques.

2. Experimental details

2.1. Structure of bulk HTS motor

The structure of a bulk HTS motor is shown in figure 1(a). The outside diameter of the bulk HTS motor is 500 mm, the length and the weight are 650 mm and 200 kg. The target specification of the motor is 30 kW with 720 rpm. The motor is a type of synchronous with an axial gap type, which is composed of single rotor plate between two stator plates without a brush. The rotor plate has eight poles of bulk of Gd123 (QMG, Nippon Steel Co.) and the diameter of bulk HTS is 60 mm. The stator plate has six armature coils those are pulsed copper magnetization coils for PFM. Presently, in addition to the previously used vortex-type coil we have employed a CMDC developed in our research group in the testing motor for the first time. To magnetize the eight poles of the bulk, the PFM was performed such that the bulk was placed between two armature coils, and cooled below the critical temperature by conduction cooling under zero-field. Pulsed current is obtained by external pulsed power supply equipment. The generation of heat from the Magnetization coil is suppressed by cooling liquid nitrogen refrigerant. The heat invasion was suppressed by employing a torque tube and the rotor was isolated in vacuum. The vacuum insulation itself is quite essential in these kinds of machines to suppress some of mechanical losses.

![Figure 1. (a) Schematic illustration of the construction of the bulk HTS motor (b) Complete system of the bulk HTS motor](image)

2.2. Cooling method of bulk HTS

A complete system of the bulk HTS motor is shown in figure 1(b). Presently, we employed a closed-cycle condensed neon circulation where the temperatures of the bulks were lower than the liquid
nitrogen temperature. The bulk HTS motor was connected with a compact GM cryocooler (Cryomech AL330) for the condensation of neon. The neon condensed at the cold head of the GM cryocooler passes through the piping and entry to circulate around the bulk inside the rotor, and bulk HTS was cooled with conduction cooling along the a-b crystallographic plane. The temperature at the bulk HTS surface reached 38 K.

2.3. Measurement system
The geometry of the Hall sensor (F.W.Bell BHT921), thermocouple, and measurement configuration are shown in figure 2 at the PFM that uses the vortex-type coil. The gap between the sensor and the bulk was 0.7 mm.

The geometry of the Hall sensor, the thermocouple, and the measurement configuration are shown in figure 3 at the PFM that uses the CMDC. The gap between the sensor and the bulk was 1.3 mm.

In the both conditions, An Au-0.07 %Fe/normal silver thermocouple was employed for measurement of the temperature.

3. Results and Discussions

3.1. PFM combined with a step cooling by using a vortex-type armature coil
In the first step, we have verified a step-cooling PFM by using a vortex-type armature coil in the motor. The structure of coil is shown in figure 4, and the coil diameter and the thickness are 84 mm and 19 mm. The material makes use of copper wire. The result is shown in figure 5. The maximum trapped magnetic flux density measured at 0.7 mm above on the surface of the bulk HTS was below 0.7 T after cooling down to 38 K. When we started the PFM at 70 K, the trapped flux density increased with the number of the applied pulse and tends to saturate below 1.0 T at 70 K. The increase of the flux was observed by lowering the temperature from 70 K to 38 K (closed circles for 3rd and 4th PFM) as shown in figure 5. As the result, the step cooling was useful with a vortex-type armature coil in the motor.
3.2. PFM by using a Controlled Magnetic density Distribution Coil (CMDC) at 38 K

To obtain a conical distribution of the trapped field and the integrated flux with the maximum trapped magnetic flux density, we employed a new type of magnetizing coil, which is a CMDC. The structure of the CMDC is shown in figure 6. The CMDC is a type of vortex coil composed of an outer solenoid coil and inner vortex-type coil. Then, the present coil has realized a control of magnetic field by choosing effective diameter of the vortex coil either 44 mm or 84 mm for the sample with 60 mm in diameter. When the outer coil and the inner are connected, it is possible to magnetize it as a coil of 84 mm in figure 6(a). It is possible to magnetize it as a coil of 44 mm as in figure 6(b) only at the whirl type coil. The thickness of the coil is 19 mm and the material makes use of copper wire. To verify the PFM with different applied magnetic fields for the field-pole bulk, the result obtained at 38 K is shown in figure 7. It is noted that the flux was measured at 1.3 mm above the surface of the bulk. The magnetic flux was able to penetrate into the centre area of bulk HTS effectively by using the CMDC. Thus, we succeeded in increasing the maximum trapped magnetic flux density together with making a distribution of trapped flux density closer to a conical shape. As a result, CMDC was proved beneficial in the actual experiment system.

Figure 4. A split-type copper coils in the vortex-coil and the HTS bulk magnet

Figure 5. The trapped magnetic flux density in the verification experiment of the step cooling. The open triangles and squares show the measured flux density values at 70 K and 38 K, respectively. The closed circles for 1st and 2nd pulses were obtained at 70 K and 3rd and 4th pulses were obtained at 38 K. The applied $B_T$: Peak value of the applied magnetic field density was 7.3 T.

Figure 6. A split-type copper coils in the CMDC and the HTS bulk magnet: (a) Coil of 84mm in diameter (b) Coil of 44 mm in diameter.
3.3. Low-temperature PFM of the step-cooled field-pole with CMDC

The step-by-step cooling temperature together with the employment of the CMDC has been successfully verified [6,7]. As the next step, we combined the step cooling with a closed-cycle condensed neon by using the CMDC. A series of the PFM procedure is shown table 1. The number of PFM was eight under different two temperatures. The first four time PFMs were performed at thigh temperature ($T_H$) and the subsequent four times PFMs were performed at lower temperature ($T_L$) than $T_H$. Both $T_H$ and $T_L$ were denoted as "65 K + 55 K" (condition I), "65 K + 38 K" (condition II), "55 K + 38 K" (condition III), and "45 K + 38 K" (condition IV) when describing in the form of "$T_H + T_L$", and the condition of magnetization temperature performed by these four combinations. These sequences and applied temperatures ($T_H$ and $T_L$) are shown in table 1. We adopt the CMDC as the magnetization coil assembled into the motor. The 1st, 2nd, 5th and 6th PFMs were performed with the CMDC with a diameter of 84 mm, and the 3rd, 4th, 7th and 8th PFMs employed a diameter of 44 mm magnetization coil. When the diameter of magnetization coil was 84 mm, applied magnetic peak field was 7.7 T and rise-time was 6.8 ms. When the diameter of magnetization coil was set to 44 mm, applied magnetic field was 9.5 T and the rise-time was 3.2 ms. Present three conditions were the optimum values in the present stage.

| PFM | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Temperature (K) | $T_H$ | $T_H$ | $T_H$ | $T_L$ | $T_L$ | $T_L$ | $T_L$ | $T_L$ |
| Applied magnetic field (T) | 7.7 | 7.7 | 9.5 | 9.5 | 7.7 | 7.7 | 9.5 | 9.5 |
| Diameter of coil (mm) | 84 | 84 | 44 | 44 | 84 | 84 | 44 | 44 |

Figure 7. The trapped magnetic flux density in the verified PFM with a CMDC at 38 K. The applied $B_T$'s were 7.7 T for effective vortex-type coil with 84 mm diameter and 9.5 T for 44 mm diameter in a CMDC.

Figure 8(a) shows the transition of the maximum trapped magnetic flux density by using a combined step cooling and CMDC. When the magnetization temperature was 55 K, the maximum trapped magnetic flux density 1.15 T was obtained. The magnetic flux was not easy to penetrate into the bulk HTS according to the diamagnetic effect of flux pinning by cool down to 38 K. In the PFM at
45 K, it becomes difficult for the flux to penetrate into the bulk HTS because of the increase of the diamagnetism effect by the pinning effect. It is thought that the trapped magnetic flux density becomes a saturation state because the pinning forces are weaker than those at 55 K, and the magnetic flux that can be trapped is fewer in magnetization at 65 K and the maximum trapped magnetic flux density decreased. As a result, the maximum tapped magnetic flux density was obtained when the PFM at low temperature ($T_L$) was executed at 38 K after the PFM at high temperature ($T_H$) was executed at 55 K. Figure 8(b) shows transition of the trapped magnetic flux density profiles when the PFM at low temperature ($T_L$) was executed at 38 K after the PFM at high temperature ($T_H$) was executed at 55 K. The trapped magnetic flux density was increased slightly after the 4th PFM. In addition, the distribution of trapped magnetic flux density came close to conical shape. In the 6th PFM, the trapped magnetic flux density progressed overall by lowering the temperature. In the 8th PFM, the trapped magnetic flux density of centre area was improved by using the coil of 44 mm in diameter. As the result, the maximum trapped magnetic flux density reached 1.3 T at the position of 1.3 mm from the bulk surface. The previous magnetic flux of the pole bulk was 0.53 T upon liquid nitrogen cooling. According to the present results, the obtained flux 1.3 T leads to the improvement of the motor torque as well as the output power. Thus, the output of the bulk HTS motor of single rotor type on which the output was 10 kW was estimated to be 25 kW by using the presently introduced cooling and magnetization technique. Both GM cryocooler based neon refrigeration and CMDC enables us a light weight and compact driving system of the bulk HTS motor.

Figure 8. (a) Transition of trapped magnetic flux density in the PFM processed as I-IV indicated in table 1, (b) The distribution of trapped magnetic flux density of when the PFM at low temperature ($T_L$) was performed by 38 K after the PFM at high temperature ($T_H$) was performed 55 K as PFM condition III.

4. Summary
The closed-cycled refrigeration of neon by using a GM cryocooler has successfully provided a low-temperature PFM of field-pole Gd123 bulk in the testing rotating machine at 38 K. Upon magnetization, a CMDC providing either large or small diameter of vortex coil was employed. Presently, either 44 mm or 84 mm of diameter of vortex was applied to the sample with 60 mm in diameter. The maximum trapped magnetic flux density over 1.3 T was obtained at 38 K by using step cooling and CMDC. 2.5 times larger flux was obtained in contrast to previous liquid nitrogen cooling. The output of the motor was enhanced to 25 kW associated with a practical closed-cycle cooling without a liquid cryogen. The employment of a GM cryocooler based neon refrigeration and CMDC enables us a light weight and compact driving system of the bulk HTS motor.

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