Test Results of an Experimental Coil with Bi-2212 Rutherford Cable for High Energy-density HTS-SMES

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Abstract. Since FY 2004, a four-year Japanese national project has been ongoing to develop an HTS-SMES as a sub-program of the Development of Superconducting Power Network Control Technology. The purpose of this project is to confirm the performance of a high energy density SMES coil with Bi-2212 cables. This coil system is composed of an NbTi outer coil and a Bi-2212 inner coil, consisting of 16 double pancakes. A Bi2212 cable of 140 m length is used for the double-pancake windings, and reinforcing materials are co-wound with the cable. A winding inner diameter of 360 mm was set according to the bending tolerance of the cable. The magnet is to be cooled at 4.2 K by liquid helium in order to obtain high overall current density. In the first year of this project, a conceptual design and various experiments for HTS magnet were carried out. This paper describes the test results of the HTS experimental coil that was developed to evaluate the electrical and thermal characteristics of an HTS. It is important to minimize deterioration and damage to the cable, because such defects cause fatal impact to the coil. Consequentially, high accuracy measurement of V-I characteristics up to $10^{-8}$ V/cm range was performed in this experiment.

1. Introduction

In 2004, a four-year Japanese national project was begun to develop an HTS SMES coil as a subprogram of the Development of Superconducting Power Network Control Technology. The purpose of HTS coil development using Bi-2212 Rutherford conductor is proceeding with a compact design of an SMES coil that can generate a high magnetic field, and to evaluate improvement in energy storage density by combining the NbTi coil. The schedule for development of the Bi-2212 coil by financial year is as follows:

- FY 2004: Basic property evaluation of the Bi-2212 coil
- FY 2005: Manufacture of 20 coils and stability examination for the laminating coil
- FY 2006: Demonstration of high stored energy for the laminating coil at high magnetic field

The coil basic property evaluation in 2004 verified the following items:

1) Voltage-Current (V-I) characteristics of coil at 64 K: Significant alteration of the superconducting properties for before-and-after the coil winding process is evaluated.
2) Voltage-Current (V-I) characteristics of coil at approximately 4 K: The critical current (I_c) and n-index of the coil at 4 K was confirmed, and the degradation of the n-index in the high accuracy range of $10^{-8}$ V/cm is evaluated.
3) Observation of coil temperature during the pulsed operation, and the AC and DC losses estimated.

2. HTS Coil

2.1. Specifications of Bi-2212 Rutherford cable

The Bi-2212 Rutherford cable was fabricated at Showa Electric Cable & Wire Co. Ltd. Specifications of the HTS cable are shown in Table 1. A critical current of approximately 10 kA was obtained for this cable at 4.2 K, self-field [1].

Table 1. Specification of the Bi2212 Rutherford Cable

| Width (mm) | 13.4 |
| Thickness (mm) | 1.55 |
| Strand diameter (mm) | 0.81 |
| Strand number | 30 |
| Pitch length (mm) | 87 |
| Metal matrix / SC ratio | 2.8 |

2.2. Coil design

Basic design parameters of the coil are shown in Table 2. The features of the coil are as follows.

1. Winding diameter - A winding inner diameter of 360 mm was set according to the bending tolerance of Bi-2212 Rutherford cable.
2. Improvement of elasticity - Reinforcing material of stainless-steel strips is co-wound with the HTS cable. Mechanical reinforcement of winding is indispensable for a high field HTS-SMES coil to avoid degradation of the superconducting characteristics.
3. Cooling method – The coil is to be cooled at 4 K by liquid helium through heat conduction plates. The kA-class current leads were cooled by two 80K-GM cryocoolers [2].

The experimental HTS coil is shown in Figure 1. Voltage taps (A6-A8) were attached on every 10-turn. Furthermore, in a part of the innermost winding (A1-A5) and the outermost winding (A9-A13) of the coil, extra taps were set at every 1-turn. Some temperature sensors were set on the coil and a hall element sensor set to coil center.

Table 2. Design parameters of the coil

| Winding                       | Double pancake |
|-------------------------------|----------------|
| Inner Diameter (mm)           | 360            |
| Outer Diameter (mm)           | 635            |
| Thickness of a coil (mm)      | 31             |
| Winding Number                | 81             |
| Inductance (H)                | 0.00408        |
| Conductor Length (m)          | 140            |
| Operating Current (A)         | 2700           |
| Maximum Field at winding (T)  | 1.71           |
| Current Density (A/mm²)       | 86.3           |
| Stored Energy (kJ)            | 14.9           |

Figure 1. Overview of the double pancake coil

Figure 2. I-V characteristics of the upper pancake coil at 64 K test
### 3. Test results

#### 3.1 V-I Characteristic test of HTS coil at 64K

V-I characteristic of the upper pancake coil at 64 K is shown in Figure 2. Symbols and lines in Figure show measured voltage and estimated voltage in each part of the coil. Estimated voltage was calculated by HTS Rutherford conductor under the characteristic of \( I_c = 420 \) A at 64 K and a self-field.

From this test, high accuracy measurement of V-I characteristics less than \( 10^{-8} \) V/cm region was performed, and it was checked that there is no descent of the n-index in this region. Therefore, it was verified that there is no HTS conductor degradation by winding process.

#### 3.2 V-I Characteristic test of HTS coil at 4 K

The temperature change of each part of the coil at 4 K is shown in Figure 3. The temperature rise of about 1.0 K at the innermost winding side, of about 0.7 K at the winding center and of about 0.8 K at the outermost winding side were measured with 3000A DC operation. The temperature rise in this test arises from the heat generation of the coil and the heat leak from the current leads. The heat generation calculated from measured voltage was about 1.1 W.

I-V characteristics of the upper pancake coil at 4 K is shown in Figure 4. It shows that generating voltages decrease gradually equivalent to increase of \( I_c \) as it goes in the direction of outer winding. This result denotes the same tendency of the 64 K test result.

Also, since the degradation behavior of n-index was not observed in Figure 4, it is concluded that there are no defects induced by the winding process. The V-I curve estimated from \( I_c(n)-B-T \) characteristics of Bi2212 wire are shown in the Figure 4 by lines. And these measured voltages consist with the estimation lines. The same behavior is shown also in the lower pancake coil.

#### 3.3 Pulsed operation

The pulse test was carried out, and the temperature changes in each part of the coil were measured. Conditions of pulsed operation are shown in Table 3. The operating current superimposed triangular-wave of 5 cycles on DC initial current. A pulse cycle and peak-to-peak amplitude of triangular-wave are 18 sec and 700 A, respectively. The examination result is shown in Figure 5. When the initial current is small, distinct temperature change corresponding to pulsed operation is shown. But if the initial current becomes large, the appearance of temperature change greatly differs. Based on the examination results, the relationship between increasing amount of magnetic field (the amount of the maximum magnetic fields which each part of a coil experiences) and the normalized heat generation of the coil (it normalized based on the coil attainment temperature of an innermost winding side) is shown in Figure 6. When the DC component of operating current is low, the heat generation of the coil is proportional to the cube of the magnetic field (\( \Delta Q \propto B^3 \)), and hysteretic loss is dominant. In the case of large initial current of 2150 A, the DC losses resulted from flux-flow was considerable.
4. Conclusion

We developed a HTS double pancake coil wound with a large current Bi-2212 Rutherford cable and evaluated the various characteristics of the HTS magnet as follows.

- Serial operation of the HTS coil with large current was successfully demonstrated.
- High accuracy measurement of V-I characteristics was carried out. It was checked that there is no descent of the n-index in this region, and it was verified that there is no HTS conductor degradation by winding.
- AC losses of the HTS coil were estimated in this experiment. For this operating condition, the hysteresis loss is dominant and the influence of flux flow loss was also checked.

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