Quench protection of DI-BSCCO coil

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Abstract

Quench protection is one of the most important requirements for the practical application of high-temperature-superconducting (HTS) coils. Quench protection requires that early detection of a developing quench event is followed by rapid reduction of the operating current. However, such quench detection is very difficult because HTS wire produces heat only locally due to the very slow propagation velocity of a normal zone. Excellent high voltage insulation performance is required if the current is to be reduced rapidly in a large-scale superconducting application with very large inductance. Thus it is important to investigate the behavior of coils with various decay time constants, and to detect voltages on very short time scales. This goal remains to be achieved. In the present study we built test coil and a full-scale pole coil for a 20 MW motor for use in experiments on quench protection, and parameterized the relation between the decay time constant and the detecting voltage, using a conventional balance circuit to detect the quench, which was generated by gradually raising the temperature of the coils. The results verify that a balance circuit can be used for quench detection. For example, when the current decay time constant is 4 seconds, the test coil can be protected even with a detecting voltage of 0.15 volts, despite a significant heat production rate of 126 W. We also confirmed that the full-scale pole coil, with a decay time constant of 20 seconds, can be protected with a detecting voltage of 0.06 V.

Keywords: Quench protection; DI-BSCCO wires; Superconducting motor; HTS coil

1. Introduction

It has recently been said that it would be environmentally helpful to use conventional electric motors to propel ships. However, such motors are not very energy-efficient, so worldwide development efforts have focused on creating highly efficient motors that use superconducting coils wound with HTS wire [1].

Generally, HTS wires have a very slow NZP (normal zone propagation) velocity, in the range of several centimeters per second [2]. Hotspots can easily occur in such a coil, resulting in its degradation. To prevent this, it is important to limit a hotspot’s temperature and any temperature gradients along the wires by detecting an incipient quench and quickly reducing the operating current. In our experiment to detect an incipient quench we have tried to use a balance circuit, which is a well known method in low-temperature-superconducting (LTS) coil, and found that a balance circuit can also detect an incipient quench in HTS.

However, a large superconducting motor in the 20 MW range [1] will have an inductance as high as 100 H, so the coil and the wiring need to have a withstand voltage of thousands of volts when the operating current diminishes rapidly. So
the authors built test coils to simulate those in a large motor, to determine how to protect the coils and prevent degradation by parameterizing the current decay time constants and the quench detecting voltages. In addition, the authors made a full-scale pole coil for a 20 MW motor and investigated the requirements for its protection.

2. Specifications of DI-BSCCO coils

The specifications of the test coil and the full-scale pole coil are listed in Table 1. Fig. 1 shows the experimental configuration of the test coil, which consisted of four circular double pancake coils wound with DI-BSCCO wires (DPC#1～DPC#4) and five copper cooling plates (Cu#1～Cu#5). Thermometers were embedded in the copper cooling plates, with four thermometers (one every 90 degrees) in the upper and lower end plates. The test coil was cooled by a refrigerator and the temperature was controlled by a heater attached to the cold head of the refrigerator. Fig. 2 shows the appearance of the racetrack coil. The full-scale pole coil consisted of four double pancake racetrack coils and five copper cooling plates. Thermometers were embedded in the copper cooling plates, for a total of 16 thermometers in Cu#1 and Cu#5. They were cooled by a refrigerator in a similar way to the test coil.

Table 1. Specifications of DI-BSCCO coil.

<table>
<thead>
<tr>
<th></th>
<th>Test coil</th>
<th>Full-scale pole coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of DI-BSCCO wire</td>
<td>Type Hi</td>
<td>Type Hi</td>
</tr>
<tr>
<td></td>
<td>Type HT(SS)i</td>
<td></td>
</tr>
<tr>
<td>Critical current of wire</td>
<td>about 180 A</td>
<td>about 180 A</td>
</tr>
<tr>
<td>Coil</td>
<td>Circular double pancake (Epoxy impregnated)</td>
<td>Racetrack double pancake (Epoxy impregnated)</td>
</tr>
<tr>
<td>Coil size</td>
<td>I.D. 70 mm</td>
<td>Width 357 mm</td>
</tr>
<tr>
<td></td>
<td>O.D. 214 mm</td>
<td>Length 1657 mm</td>
</tr>
<tr>
<td></td>
<td>Height 9.7 mm</td>
<td>Height 9.7 mm</td>
</tr>
<tr>
<td>Number of stacked coils</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total length of wire</td>
<td>880 m</td>
<td>13000 m</td>
</tr>
<tr>
<td>Total number of turns</td>
<td>2000 turns</td>
<td>4000 turns</td>
</tr>
<tr>
<td>Maximum parallel field</td>
<td>4.2 T</td>
<td>5.7 T</td>
</tr>
<tr>
<td>Maximum perpendicular field</td>
<td>2.0 T</td>
<td>2.5 T (Round part)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 T (Straight part)</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.4 H</td>
<td>15 H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>8.2 kJ at 200 A</td>
<td>300 kJ at 200 A</td>
</tr>
<tr>
<td>Cooling plates</td>
<td>Copper (3t)</td>
<td>Copper (3t)</td>
</tr>
</tbody>
</table>

3. Experiment

3.1. Experimental method

We investigated the protection of DI-BSCCO coils from degradation, including the test coils and the full-scale pole coils, by parameterizing their current decay time constants and quench detecting voltages. As shown in Fig. 3 and Fig. 4, balance circuits were used to detect a quench.

The quench detection time was 0.1 second. To initiate a quench, the operating current was kept at 200 A and about 30 K, and the temperature of the coils was gradually raised while maintaining a temperature difference of less than 0.5 K between the upper and lower ends. When a quench was detected, in the case of the test coils the operating current was reduced exponentially by a function generator, because it would not naturally decay so rapidly due to the coil’s small inductance. In contrast, in the case of the full-scale pole coil the operating current was diverted through a dump resistor. After a quench, I-V characteristics were measured. Comparison with the initial I-V characteristics revealed the extent of degradation, if any.
3.2. Experimental results

3.2.1. Test coil

The test coil was found to degrade with a current decay time constant of 4 seconds and a quench detecting voltage of 0.16 V. The results are shown in Fig. 5. The maximum temperature of the test coil was about 125 K and the generated voltage reached about 14 V in DPC#1 [4]. When the current was broken, the heat production rate in the test coil was about 132 W. When the maximum voltage of the normal zone was about 14 V, the operating current was about 79 A. This indicated that the normal zone resistance was about 0.2 ohm. It was estimated that the normal zone length was about 20 meters by calculation based on the electrical resistivity of silver at 110 K, which is the critical temperature of DI-BSCCO wire.

We investigated the divided area of DPC#1 in Fig. 6 to determine which part degraded. Additional voltage taps were added and each I-V curve was measured. Degradation was found only at the Vmid region shown in Fig. 7. It is estimated that the degradation area resembled the painted area in Fig. 6, because the temperature rise was found only at Cu#1-0° and the normal zone extended for about 20 m of the wire’s length. The perpendicular magnetic field was highest within the coil at the degraded area. It is considered that a part of the area that generated the most heat was quenched and degraded. Now we shall discuss the degradation mechanism in detail. As is well known, the degradation of the wire was caused by stress induced by change in the thermal expansion coefficient as the temperature increased. Dr. K. Osamura reported that the critical current of DI-BSCCO wire decreases to less than 95% of normal when the compressive strain is more than 0.25%. Based on this report, we estimated that when the coil underwent degradation, the temperature of the hotspot was higher than approximately 250 K.

3.2.2. Full-scale pole coil

When the full-scale pole coil showed degradation, the current decay time constant was 40 seconds and the quench detecting voltage was 0.06 V, as shown in Fig. 8. The maximum temperature of the full-scale pole coil was about 52 K and the generated voltage reached about 45 V in DPC#4. When the current was broken the heat production rate in the full-scale pole coil was about 42 W. Significant degradation was found in DPC#1, with a burnout at the center of the straight portion of the racetrack coil.
3.3. Discussion of results

Fig. 9(a) shows the relation between the current decay time constant and the detecting voltage of the test coil. In the test coil, when the current decay time constant was 4 seconds and the quench detecting voltage was 0.15 V, the heat production rate in the coil was about 120 W. The coil was protected from degradation. There are two reasons for this excellent stability. One reason is that DI-BSSCO wire is homogeneous in terms of critical current. Another reason is that the coil allowed good heat transfer between adjacent turns because it was impregnated with an epoxy resin. When the current decay time constant was 10 seconds and the quench detecting voltage was 0.06 V, the coil was protected. When the current decay time constant was 20 or 30 seconds and the quench detecting voltage was 0.05 V, the coil was protected. Fig. 9(b) shows the behavior of the full-scale pole coil. The conditions required to protect the full-scale pole coil did not differ greatly from those for the test coil. This means that coil protection depends on the heat production rate in the hotspot, but not on the size of coil.

4. Conclusion

We investigated quench protection for DI-BSCCO coils, and found the required relation between the detecting voltage and the decay time constant for coil protection. The test coil experiments prove that when the current decay time constant is shorter, coils can be protected from degradation even with a higher detecting voltage. A full-scale pole coil can also be protected by conditions similar to those that protected the test coil. Even when the heat production rate was high, DI-BSCCO coils showed very stable operation because of their homogeneity with respect to critical current and the good heat transfer between adjacent turns.

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Reference