Design and Test of a Thermal Triggered Persistent Current System using High Temperature Superconducting Tapes

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Abstract. A superconducting magnet which is operated in persistent current mode in SMES, NMR, MRI and MAGLEV has many advantages such as high uniformity of magnetic field and reduced thermal loss. A high temperature superconducting (HTS) persistent current switch (PCS) system was designed and tested in this research. The HTS PCS was optimally designed using two different HTS tapes, second generation coated conductor (CC) HTS tape and Bi-2223 HTS tape by the finite element method (FEM) in thermal quench characteristic view. The CC tape is more prospective applicable wire in these days for its high h value and critical current independency from external magnetic field than Bi-2223 tape. Also a prototype PCS system using Bi-2223 tape was manufactured and tested. The PCS system consists of a PCS part, a heater which induces the PCS to quench, and a superconducting magnet. The test was performed in various conditions of transport current. An initial current decay appeared when the superconducting magnet was energized in a PCS system was analyzed. This paper would be foundation of HTS PCS researches.

1. Introduction

Many superconducting applications such as SMES, MAGLEV and MRI require the persistent current mode to operate with no loss and high uniformity. To make the persistent current mode, the system needs a switch made of superconducting tape. PCS is quenched by cryogenic heater [1]-[3]. YBCO CC and Bi-2223 tapes are used for the PCS design in this research. A heater is required to heat up the PCS to the critical temperature of the HTS tape [4]. The optimal heater energy was calculated by thermal analysis using the finite element method (FEM). Also, a PCS system using Bi-2223 tape was fabricated with double pancake type load wound by Bi-2223 HTS tape. The PCS system was tested in various charging current conditions. The steep initial decay of charging current was showed in the test results of higher charging current than the critical current of magnet load. In this paper, a PCS using two different HTS tapes was designed and the operating characteristic include initial decay of PCS system using Bi-2223 was analyzed.
2. Design of Persistent Current Switch

2.1. Design of Persistent Current Switch

Figure 1 is a schematic of the whole PCS system. The PCS and superconducting magnet operated in liquid nitrogen, 77 K. The energy loss, $E_s$, is generated in the PCS part when the charging current is applied to the superconducting magnet from the MPS. Therefore, we have to apply the energy, $E_0 + E_s$, to charge the superconducting magnet up to the target energy, $E_0$. The ratio of energy loss represented as follows

$$\frac{E_s}{E_0} = \frac{R_s \cdot I_0^2 \cdot t}{\frac{1}{2} L \cdot I_0^2 \cdot R_f \cdot t} = \frac{2L}{R_f \cdot t} \tag{1}$$

From Eq. 1, the energy loss could be reduced by enlarging the $R_s$, the resistance of normal state of PCS and $t$, the ramping up time of charging current. The optimal length of PCS to limit the energy loss below $x\%$ could be calculated from Eq. 2

$$l_s \geq \frac{200 \cdot L \cdot A_s}{x \cdot t \cdot \rho_s} \tag{2}$$

where, $l_s$ is the length of PCS, $L$ is the inductance of superconducting magnet, $A_s$ is the cross section area of HTS tape, $I_0$ is the flowing current in superconducting magnet, $I_s$ is the flowing current in PCS, and $\rho_s$ is the resistivity of HTS tape in normal state. Consequently, the optimal length from an economic viewpoint of PCS was calculated as 1.2 m. The PCS was made by reinforced Bi-2223 HTS tape.

2.2. Design of Heater for Persistent Current Switch

The heater for the PCS was made of NiCr which has a unit resistance of 33 $\Omega$/m and it was wound around the innermost side of the bobbin. The HTS tape was wound on the heater. Then teflon tape and foam were stuck on the outermost side to enhance the heat transfer from heater to PCS. To analyze the temperature distribution in the PCS, FEM tool was used. For fast and simple analysis, a quarter of the PCS bobbin was simulated and its cut surface was calculated in the adiabatic condition. Figure 2(a) is the simulation result when the heater current is 1.3 A, 67 W, for the Bi-2223 HTS tape. The temperature of the HTS tape increased up to 112 K in 1 second. The PCS should be quenched in a second in this condition because BSCCO has a $T_c$ of about 110K. Figure 2(b) is the simulation result for the PCS using the YBCO CC when the heater current is 0.7 A, 19.4 W. The temperature of the CC increased up to 93 K in 1 second. YBCO has a $T_c$ of 93K. So the PCS should be quenched in a second as Bi-2223 at 1.3 A of transport current. Though the aimed temperature of YBCO is lower than Bi-2223 for its critical temperature difference, it is not an only reason. CC has silver and copper stabilizer on YBCO while Bi-2223 tape has silver and stainless steel on BSCCO. Because copper has higher thermal conductivity than stainless steel, CC has better thermal characteristic.
Figure 2. 3D simulation results of (a) Bi-2223 tape with 1.3A heater current after 1sec, (b) YBCO CC tape with 0.7A heater current after 1sec.

3. Experiment of Persistent Current Switching System
The characteristics of persistent current were observed with respect to various charging current magnitude. The magnet is a series connected 2 double pancake coils which have a critical current of 50 A and a charging current was 10 A and 50 A. And the persistent current was measured by hall sensor from superconducting magnet. All experimental data were acquired by DC amplifier and LabVIEW board. Figure 3 is the picture of prototype Bi-2223 HTS PCS system.

Figure 3. Assembly of prototype Bi-2223 PCS system

3.1. Test results with Various Charging Currents
The closed system was composed of superconducting magnet and PCS. Firstly, the PCS was heated up enough to quench by heater. When the charging current reached the target value, the heater was turned off. The charging current was bypassed to the PCS and then the closed circulating current flowed into the PCS system. Finally, the closed persistent current system was accomplished after separating the MPS from system. When the charging current was smaller than the critical current value of 50 A, the initial current decay was not predominant, but the charging current was closer to the critical current value of 50 A, the circulating current was abruptly decreased within 1,500 sec. Therefore, the initial decay of persistent current is deeply dependent upon the magnitude of charging current. These results are shown in figure 4. The joint resistance was 320 nΩ from 10 A test without flux creep effect.
3.2. Analysis of Initial Decay considering n-value
The initial circulating current was drastically decreased when the magnitude of charging current was closed to the magnitude of critical current. This steep decrease is mainly due to the resistance in the flux creep range and its low n-value which is caused from bad joint characteristic. Therefore, the magnitude of charging current was very important to operate the persistent current mode. The initial current decay is characterized by the flux creep resistance and n-value.

4. Conclusion
HTS PCS could be used in many superconducting applications. The switching part of the PCS system is made of HTS tape. Optimal heating energy is required to quench by thermal triggering. 67 W and 19.4 W of heater energy are calculated to Bi-2223 and CC tape respectively in this research by analysis using the FEM. Because YBCO CC has lower critical temperature and has a copper stabilizer of higher thermal conductivity, CC tape needs lower heater energy. YBCO also has higher n-value. So, YBCO CC is superior to PCS applications. PCS system using Bi-2223 was fabricated and tested. Because the load which had joint resistance had low n-value, the initial decay of the charging current was steep in the flux creep area. To develop a highly efficient PCS system, YBCO CC would be used for the PCS and it would require a good joint characteristic between HTS tapes.

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