

Fabrication and Test of Persistent Current Switch for HTS Magnet System

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Abstract-- This paper deals with the characteristics of persistent current switch (PCS) system for applied HTS magnet system. To apply the high-Tc superconductor in superconducting machine such as motor, generator, MAGLEV, MRI, and NMR, the study on high-Tc superconducting persistent current mode must be performed. In this experiment, the PCS system consists of superconducting magnet, PCS and magnet power supply. The superconducting magnet was fabricated by connecting four double pancake coils (DPCs) in series. The PCS was inductive double pancake coil type and heated up by the SUS 303L tape heater. The optimal length of PCS was calculated and thermal quench state of PCS was simulated by using finite element method(FEM) and compared with experimental results. The optimal energy to normalize the PCS was calculated and introduced. Finally, the persistent current was observed with respect to various ramping up rate and magnitude of charging current.

1. INTRODUCTION

Generally, the applied superconducting machines such as MRI, NMR and MAGLEV are operated in persistent current mode because the excellent homogeneity and stability. As the magnetic characteristics of high-Tc superconductors is more stable at low temperature and generate higher magnetic field than low-Tc superconductor, the high-Tc superconductor is expected to promising material to apply to many fields. Under these requirements of investigation, the high-Tc superconducting PCS switch system is studied in many countries. In this paper, prototype superconducting magnet and PCS was fabricated, tested and shown the experimental and simulation results. Firstly, we designed the superconducting magnet by using FEMLAB and determined the critical current and inductance of prototype superconducting magnet as about 65 A and 6.5 mH respectively. The PCS was heated up by the SUS 303L heater wound below the PCS layers. The operational conditions of PCS were calculated and the heated up temperature of PCS was simulated by FEMLAB and compared with measured temperature. Finally, the results of persistent current were shown and analyzed.

2. HIGH-Tc SUPERCONDUCTING MAGNET

2.1. Design of Superconducting Magnet

The superconducting tape was reinforced by SUS 315L to fabricate superconducting magnet. The superconducting magnet load consists of four DPCs and connected by PbSn paste solder with series. The piece length of each double pancake coil was 19.2 m and the inner diameter of magnet

TABLE I
SPECIFICATIONS OF PROTOTYPE SUPERCONDUCTING MAGNET

Total Height	0.036 m
Inner Diameter	0.099 m
Outer Diameter	0.1186 m
Kapton Thickness	0.000335 m
Wire Length	19.2 m × 4 ea

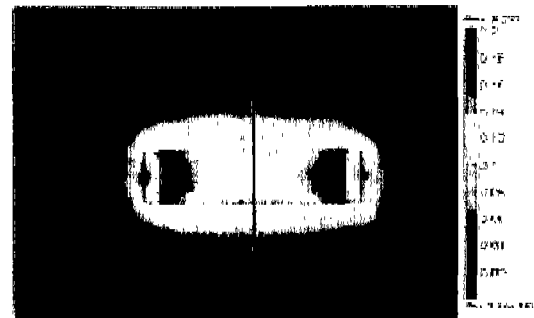


Fig. 1. Distribution of magnetic field in superconducting magnet at 50 A.

was 0.099 m. The design parameters of superconducting magnet load were shown in table 1. The magnetic characteristics of superconducting magnet was simulated by using FEMLAB.

Fig. 1 shows the 2-D distribution of magnetic flux density in superconducting magnet when the 50 A flows through the magnet. The critical current of superconducting magnet is dominantly determined by the magnetic field. From this simulated magnetic field, we could estimate the critical current and inductance of magnet.

2.2. Fabrication of Superconducting Magnet

The reinforced wire was used to enhance the mechanical characteristics. The reinforced wire was coated by the SUS 315L tape at both sides. Table. 2. shows the specifications of reinforced wire. Because the resistance of SUS 315L is relatively larger than resistance of matrix, we stripped off the SUS 315L by soldering iron. To minimize the joint resistance, we adjust the joint length by 5 cm. This joint method can maintain the mechanical strength of magnet.

2.3. Characteristic Results of Superconducting Magnet

Experimental test of superconducting magnet was performed and compared with the simulation results. The inductances of each DPCs were all about 660 H and the inductance of whole magnet was about 6.52 mH. It corresponds to the simulation inductance 6.4 mH. This result was represented at table. 3. The comparison with experimental and simulation results were shown as table 4.

TABLE □
SPECIFICATIONS OF REINFORCED WIRE

Wire	Bi-2223/AgMg
Thickness	0.000305 m
SUS Thickness	0.000097 m
Width	0.0041 m
Ic @ 77 K	115 A
Max. Stress	265 MPa (Perpendicular to the tape)
Laminated Material	SUS 315L



Fig. 2. Picture of superconducting magnet connected in series

The measured inductance and induced magnetic flux density were agreed well with the simulation results. Moreover, consider the effect of degradation of critical current caused by bending diameter and joints, the difference of result was so reasonable.

3. HIGH-Tc SUPERCONDUCTING MAGNET

3.1. Design of Persistent Current Switch

The energy loss E_s is generated in the part of PCS when the charging current is applied to the superconducting magnet from the magnet power supply. Therefore, to charge the

TABLE □
SPECIFICATIONS OF DPCs

DPC	Inductance	Resistance @ 300 K	Ic @ 77 K
#1	661 μ H	0.85 Ω	65 A
#2	660 μ H	0.82 Ω	65 A
#3	675 μ H	1.1 Ω	68 A
#4	670 μ H	1.1 Ω	66 A

TABLE □
COMPARISON WITH MEASUREMENT AND SIMULATION RESULTS OF SUPERCONDUCTING MAGNET

	Measurement	Simulation
Inductance	6.52 mH	6.4 mH
Magnetic Flux density (@ 1 cm upper point from centre of the reactor, 50A)	0.085 T	0.09 T
Ic @ 77 K	60 A	73 A

superconducting magnet to the target energy E_0 , we have to apply the energy as $E_0 + E_s$. The ratio of energy loss represented as follows

$$\frac{E_s}{E_0} = \frac{R_s \cdot I_s^2 \cdot t}{\frac{1}{2} \cdot L \cdot I_0^2} = \frac{2 \cdot L}{R_s \cdot t} \quad (1)$$

From this equation, the energy loss could be reduced by enlarging the R_s , the resistance of normal state in PCS and t , the current ramping up time. The optimal length of PCS of limiting the energy loss to $x\%$ could be presented as follows from (1).

$$l_s \geq \frac{200 \cdot L \cdot A_s}{x \cdot t \cdot \rho_s} \quad (2)$$

l_s is length of PCS, A_s is cross section area of superconductor, L is inductance of superconducting magnet, I_s is flowing current in PCS, and ρ_s is the resistivity of superconductor in normal state. So the optimal length of PCS 1.8 m could be calculated from (2). The bobbin size of PCS is same as the bobbin of superconducting magnet

3.2. Design of Heater for Persistent Current Switch

It is so important to decide the minimum energy to heat up the PCS. In this investigation, Minimum energy to heat up the PCS was calculated by FEMLAB, FEM tool. We wound the SUS 303L heater tape at the bottom of the bobbin and wound the PCS and then wound the teflon tape to enhance the heat conductivity between heater and PCS. The simulation parameters of PCS are shown in table 5 and the result is fig. 3. The necessary minimum energy to heat up the PCS to be quench temperature of 110 K is about 9 W.

3.3. Fabrication of Persistent Current Switch

The persistent current switch was wound as double pancake coil type magnet. The length of persistent current was 1.8 m which was calculated by (2). The PCS was electrically isolated from heater by kapton tape. The V-I characteristics of PCS was as following fig. 4. The critical current of PCS was about 115 A which was not degraded by bending. Therefore, the critical current of persistent current was determined by superconducting magnet of 60 A.

TABLE V
SPECIFICATIONS OF HEATER FOR PCS

Heater	Material	SUS 303L
	Length	3 m
	Thickness	100 μ H
	Width	0.0041 mm
	Resistance @ 77K	2.24 Ω
Operation Current		2 A

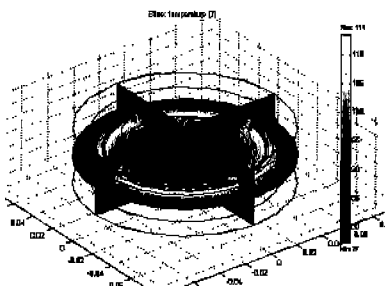


Fig. 3. Distribution of temperature of PCS for $I_h = 2$ A.

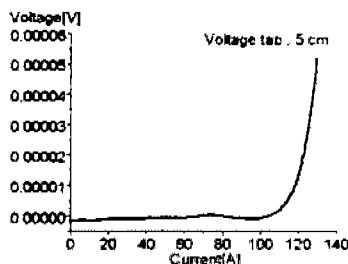


Fig. 4. V-I Characteristics of PCS

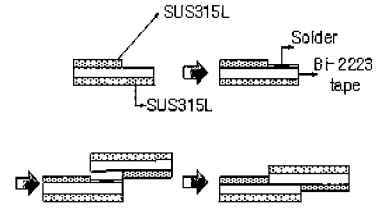


Fig. 5. Joint Procedure of Reinforced Wires



Fig. 6. Cross section view of HTS wire (a) Reinforced wire by SUS315L (up) (b) Non-reinforced wire (down)

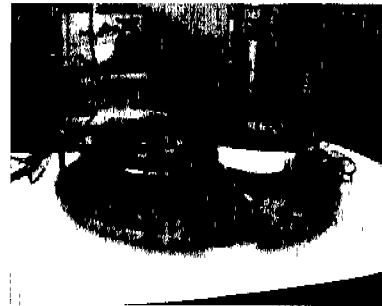


Fig. 7. Picture of persistent current mode system

4. FABRICATION OF PERSISTENT CURRENT MODE SYSTEM

4.1. Fabrication of Persistent Current Mode System

The superconducting magnet and PCS are made by reinforced wire. The SUS terminals of the PCS and superconducting magnet were stripped off and then jointed

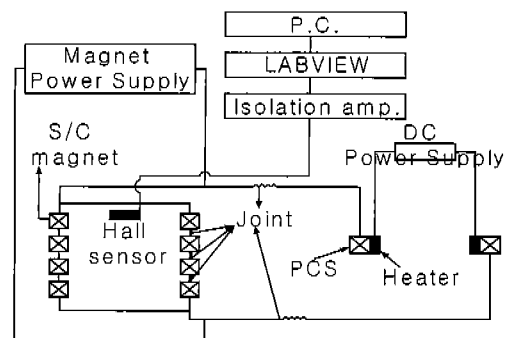


Fig. 8. Schematic diagram of the experimental system each other. The jointed length is about 8 cm to minimize the joint resistance. The procedure of joint is as following fig. 5.

The terminals were jointed by 63Sn/37Pb paste solder. The picture of persistent current mode system is shown in following fig. 7. The picture of reinforced wire used in this study was shown in fig. 6.

5. EXPERIMENTAL SETUP

In this study, the characteristics of persistent current are investigated with respect to various conditions. The ramping up rate is adjusted from 0.1 A/s to 0.5 A/s and magnitude of charging current is adjusted from 30 A to 120 A. The persistent current showed different characteristics with respect to each experimental condition.

The heater for PCS was heated up by HP 6253A dc power supply and the superconducting magnet was charged by Lake Shore 623 magnet power supply. The T type thermocouple was used to detect the temperature of PCS and transverse type cryogenic hall sensor was used to measure the magnetic flux density induced by the persistent current in the centre of the superconducting magnet. Fig. 8 shows the schematic diagram of the experimental system. All experimental signals through the isolation amplifier are monitored through the data acquisition board. Data acquisition is carried out with LAB-VIEW. The shunt resistors are installed to measure the current flowing through the heater and the superconducting magnet. All signals are passed through the isolation amplifier and low-pass filter.

6. EXPERIMENTAL RESULTS

This paper deals with the characteristics of persistent current with respect to various operation conditions. Moreover, thermal quench state of PCS was simulated by using FEM tool.

At first, the PCS was heated up by SUS heater with 2 A, and then ramped up the charging current to the superconducting magnet.

When the ramping up current reached at the target current, turn off the heater and let the charging current bypass into the PCS. The persistent current circulates the closed circuit after disconnecting the MPS from the PCS system.

The circulating persistent current showed peculiar characteristics due to magnitude of charging current but similar characteristics due to speed of ramping up time. In this study, the ramping up rate was applied as 0.1 A/s and 0.5 A/s and the charging current was applied as 40, 80, and 120 A, respectively. The results were given at fig. 9.

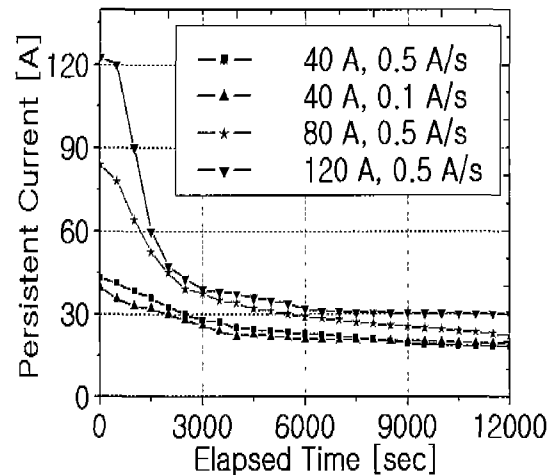


Fig. 9. Characteristics of persistent current with respect to various conditions

7. CONCLUSIONS

In this investigation, the critical current of whole system was determined by the I_c of superconducting magnet, 60 A. The magnitude of applied current was 40, 80, and 120 A, respectively. The current was drastically decreased from the beginning to 2,000 sec, and then maintained persistent current at later. In case of range of above the critical current, 60 A, the initial current attenuation was more significant. This is occurred by the flux flow resistance and more details were described in many other papers [1, 2].

The magnitude of maintained persistent current has no relationship with the initial magnitude of charging current and the maintained persistent current was about half critical current. On the other hand, the characteristics of persistent current has no difference with respect to ramping up speed. But the rapid ramping up speed is not good to superconducting magnet from the viewpoint of magnet protection. Moreover, the thermal quench state was simulated by FEM, so the PCS could be designed properly. The appropriate energy to heat up the HTS PCS was calculated more than 9 W at least.

These encouraged results could be used in many superconducting applications like insert magnet for NMR and PCS for SMES, and so on.

ACKNOWLEDGMENT

This work was supported by Korea Research Foundation Grant. (KRF-2001-041-E00138)

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