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Cooling Characteristics of Sub-cooled Nitrogen Cryogenic System for 6.6kV/200A Inductive Fault Current Limiter

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Abstract—**In this investigation, the 6.6kV/200A Inductive Superconducting Fault Current Limiter (SFCL) was designed and fabricated. The type of DC reactor for Inductive SFCL was determined as solenoid type during the period of 1st year research. The 5 bobbins for DC reactor were fabricated and each bobbin was wound with 4 stacked High-Tc superconducting (HTS) tapes and the 5 bobbins were connected in series. The critical current and inductance of DC reactor were simulated by Finite Element method (FEM) and compared with the measured results. The characteristics of DC reactor were enhanced in sub-cooled nitrogen system rather than in liquid nitrogen system. The procedures to accomplish the sub-cooled nitrogen system and the experimental results were introduced in detail. Moreover, the design of sub-cooled nitrogen cryogenic system for next year research was introduced in brief.**

1. INTRODUCTION

The several applied superconducting equipments like generator, motor, and superconducting Fault Current Limiter (SFCL) are planned to develop commercial machines until 2011 in Republic of Korea. The design and fabrication method of 3.3 kV/80 A class SFCL was developed in first year research (2001 ~ 2002). The developed inductive SFCL in first year adopted the conduction-cooled cryogenic system with GM cryocooler. The short circuit test was performed at 20 K and the experimental results were announced in another paper [1]. The conduction-cooled cryogenic system showed very unreliable thermal stability. Therefore, it is very difficult to adopt the conduction-cooled system to applied superconducting equipment with very large current variation like SFCL. The large current variation in superconducting system will cause the thermal instability. And the thermal instability will cause the critical current degradation of superconducting magnet system. The thermal instability of superconducting magnet means the decisive unstable and unreliable system. Therefore, the reliable thermal stability is very important factor for designing and fabricating the applied superconducting system.

Consequently, the sub-cooled nitrogen cryogenic method is more appropriate for applied superconducting system like SFCL than conduction-cooled cryogenic method [2]. We designed and fabricated the sub-cooled nitrogen cooling system for 6.6 kV/200 A inductive SFCL in 2nd year research (2002 ~ 2003). The thermal stability of superconducting magnet in liquid nitrogen was remarkably enhanced rather than in conduction-cooled cooling system because of large specific heat of liquid nitrogen. The experimental results of sub-cooled cooling test were successful. Moreover, the critical current of superconducting magnet in sub-cooled nitrogen was about 1.5 times as large as the critical current in saturated liquid nitrogen. In this paper, we detailedly introduced how to design and fabricate the sub-cooled nitrogen cooling system.

2. HIGH -TC SUPERCONDUCTING TAPE

2.1. Characteristics of High-Tc Superconducting Tape

In this investigation, two kinds of HTS tape manufactured by American Superconductor Corporation (AMSC) were used. The reinforced tape was used to wind the superconducting solenoidal DC reactor and the non-reinforced tape was used to reduce the resistance of cooper block. These are expressed in followings.

2.1.1. Non-reinforced Tape

The non-reinforced tape means the traditional BSCCO-2223 tape. The characteristics of non-reinforced tape were specified in table 1. The DC reactor consists of five bobbins connected in series. The five bobbins were connected by using copper blocks respectively. And the terminal ends of DC reactors were attached with non-reinforced tape too. The amount of heat generation induced by flowing current could be minimized by using these assistant HTS tapes. The research on assistant HTS tape should be studied more detailedly.

The tapes were attached to copper blocks with PbSn paste solder. The resistance of copper block with HTS tape was remarkably reduced rather than resistance of bare copper block. The copper block is called current linker. This attached HTS tape could enhance the thermal

TABLE I
CHARACTERISTICS OF NON-REINFORCED TAPE

Thickness	0.21 mm
Width	4.1 mm
Critical Tensile Stress	65 MPa
Critical Tensile Strain	0.15 %
Critical Bending Diameter	100 mm
Critical current @ 77 K	115 A
Piece Length	200 m

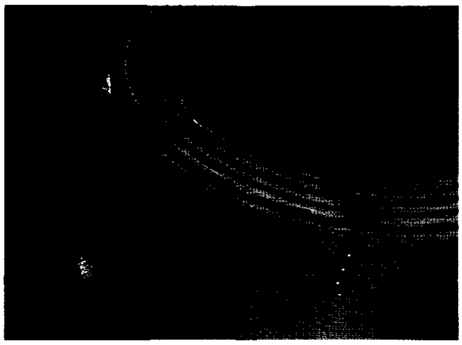

Fig. 1. The current linker enhanced by HTS tape.

TABLE II
CHARACTERISTICS OF REINFORCED TAPE

Thickness	0.30 mm
Width	4.1 mm
Critical Tensile Stress	265 MPa
Critical Tensile Strain	0.4 %
Critical Bending Diameter	70 mm
Critical current @ 77 K	115 A
Piece Length	200 m

stability of cryogenic system.

The surface of non-reinforced tape was coated by thin alumina layer. The coated alumina layer causes the increase of resistance. To minimize the resistance of current linker, the layer was removed by sand paper.

2.1.2. Reinforced Tape

The reinforced tape was coated by thin SUS 316L films. The characteristics of reinforced tape were shown in table 2. The mechanical strength characteristics of this kind of tape are enhanced by coated SUS layers. This reinforced tape is more suitable for large scale application e quipments rather than non-reinforced tape for its mechanical robustness. The double pancake coil (DPC) used in first year research was fabricated by DPC winding machine developed by Yonsei University. The DC reactor type of 2^{nd} year research was solenoid type magnet. Therefore, we developed the winding machine for solenoid type magnet. The winding job for solenoid magnet was shown in Fig. 2.

Fig. 2. The picture of winding the DC reactor.

TABLE III
PARAMETERS FOR DESIGNING THE DC REACTOR

Num. of Bobbin	Dia. (mm)	Height (mm)	Turns	L (mH)	Length (km)
1	600	636	106	4.4	0.8
2	640	594	99		1.6
3	680	558	93	63.8	2.4
4	720	528	88		3.2
5	760	498	83	103.8	4

The reinforced tape was very profitable to wind the solenoid type DC reactors.

3. DCREACTOR

3.1. Design of DC Reactor

The moderate inductance for 6.6 kV/200 A inductive SFCL was simulated as 100 mH. Therefore, we designed the 100 mH class DC reactor with 4 km in length HTS tape. The design parameters of DC reactor were shown in table 3. The FEM tool, FEMLAB was used to simulate the inductance of DC reactor.

3.2. Fabrication of DC Reactor

The superconducting DC reactor consists of 5 bobbins which were connected in series and each bobbin is wound with 4 stacked reinforced tapes. The width of groove of GFRP bobbin for winding was about 4.5 mm. the width of groove was wider than the width of HTS tape for the convenience of winding. The specifications of 5 bobbins for DC reactor are shown in table 4. The total inductance of solenoid type DC reactor connected in series with 5 bobbins was about 84 mH. The 4 stacked wire length wound with each bobbin was about 720 m and then, the total wire length wound with DC reactor was about 3.6 km. Because of the shortened total length of HTS tape and the thickness of groove, the measured inductance became smaller than simulated one. The dummy bobbin made of

TABLE□
PARAMETERS OF THE FABRICATED DC REACTOR

Num. of Bobbin	Dia. (mm)	Height (mm)	Turns per a stack	Total Inductance (mH)	Length (km)
1	600	800	93	84 mH	0.72
2	640	800	88		1.44
3	680	800	83		2.16
4	720	800	78		2.88
5	760	800	73		3.6

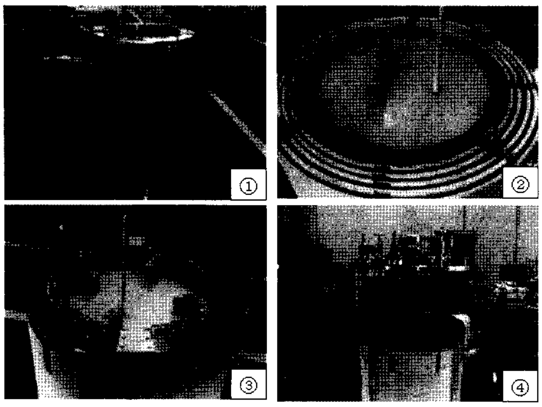

Fig. 3. The assembly procedures of DC reactor.

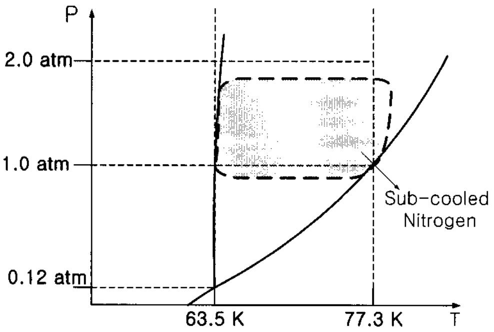

Fig. 4. The area of sub-cooled nitrogen.

G-10 was inserted into the DC reactor to reduce the total amount of sub-cooled nitrogen. The amount of sub-cooled nitrogen should be the load of GM cryocooler. Therefore, the amount of sub-cooled nitrogen in cryogenic system was optimized with the dummy bobbin. The assembly procedures of DC reactor were shown in Fig. 3. And the specifications of the manufactured DC reactor and the measured inductance were shown in table 4. The length in table 4 means the integrated length.

4. SUB-COOLED NITROGEN SYSTEM

4.1. Principle of Cooling System

The pressure conditions of saturated liquid nitrogen are 1 atm at 77 K. The area of sub-cooled nitrogen was shown in Fig. 4. In this experiment, the conditions for cryogenic system were decided as 64 K and 1 atm. The cooling characteristics of cryogenic system were compared with respect to various cooling methods. The characteristics like critical current, thermal conductivity and electrical insulation of HTS tape are enhanced in sub-cooled nitrogen rather than saturated liquid nitrogen.

4.2. Experimental Setup

The cooling capacity of cryocooler was 120 W at 80 K. Therefore, the heat load must be smaller than this value.

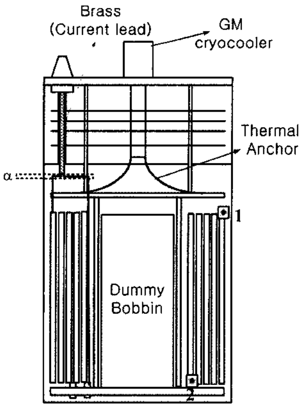

Fig. 5. The schematic drawing of cryogenic system and the locations of temperature sensors.

The calculated heat load of DC reactor system was about 87 W. This value was calculated in case of the condition of liquid nitrogen level is below the α, the location of horizontal current lead. The cooling experiments were performed in case of the level of liquid nitrogen was below the α and above the α respectively. And the total heat load estimated from the experimental cooling time was compared with the calculated one. The total heat load was calculated from the (1) and (2).

$$Q_{cond} = kA\frac{dT}{dx}\ [W] \tag{1}$$

$$Q_{rad} = \varepsilon\sigma A(T_s^4 - T_{surr}^4)\ [W] \tag{2}$$

where, k is the thermal conductivity, A is the heat transfer area normal to the direction of the heat transfer, dT/dx is the temperature gradient, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, T_s is the temperature of completely enclosed system, and T_{surr} is the temperature of separated by a gas. (1) represents the heat load induced by the conduction and (2) shows the heat load induced by the radiation.

The specifications of the current lead are shown in table 5 and the Fig. 6 shows the appearance of the current lead.

5. EXPERIMENTAL RESULTS

The heat loss is mainly due to the heat generation from the current lead. The current lead consists of vertical and horizontal parts. Therefore, the location of

TABLE V
THE SPECIFICATIONS OF THE CURRENT LEAD

Material	Brass
Diameter	12 mm
Length	310 mm
Insulator	G-10
Heat Loss	25 W

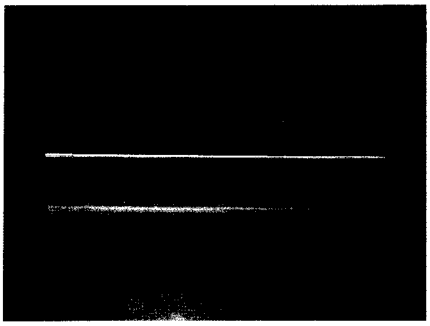

Fig. 6. The appearance of the current lead.
Up : The current lead made of brass
Down : G10-Insulator

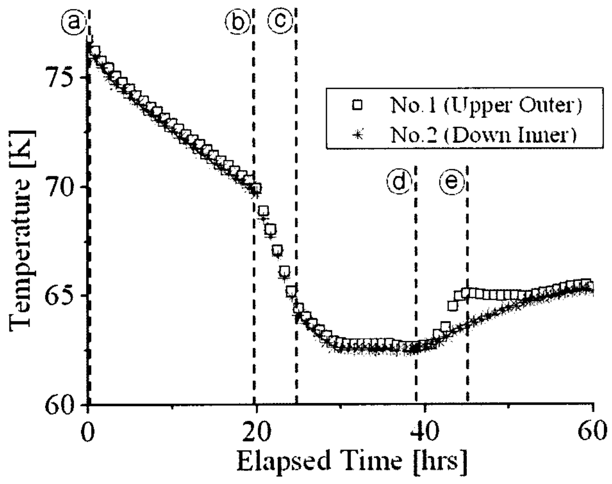

Fig. 7. The temperatures characteristics of DC reactor w.r.t. time.

TABLEVI
THE SEQUENCES TO ACHIEVE THE SUB-COOLED NITROGEN STATE

Sequence	Operation	Date
ⓐ	Turn on the GM cryocooler	06/23/2003, 13:30
ⓑ	Turn on the rotary pump	06/24/2003, 09:30
ⓒ	Turn off the rotary pump	06/25/2003, 02:20
ⓓ	Turn off the GM cryocooler	06/25/2003, 16:00
ⓔ	Inject the gas helium	06/25/2003, 21:00

horizontal current lead is very important to decide the total amount of the heat loss. The Fig. 7 shows the cooling characteristics of sub-cooled nitrogen cryogenic system for 6.6 kV/200 A inductive SFCL. Firstly, we cooled down the temperature of system by using the GM cryocooler and then, cooled down the temperature of system by using the GM cryocooler and rotary pump simultaneously. The sub-cooled nitrogen state could be achieved within 25 hours. The detail cooling methods were described in table 6. The temperature of DC reactor was cooled down from 77 K to 70 K during 20 hours by using GM cryocooler. But the temperature of DC reactor was cooled down from 70 K to 64 K during just about 5 hours by using GM cryocooler and rotary pump simultaneously. In this experiment, we found that the temperature of the cryogenic system could be cooled down with decompressing work. Therefore, the total cooling time could be estimated from the Fig. 7 as about 11 hours by using GM cryocooler and rotary pump simultaneously. At the point ⓒ, we turned off the rotary pump and cooled down the cryogenic system by only GM cryocooler and observed the cooling characteristics. The liquid nitrogen was frozen and the temperature was saturated at 63 K. Therefore, we turned off the GM cryocooler at the point ⓓ and the temperature of DC reactor became 64~65 K after 5 hours later. The amount of liquid nitrogen in cryogenic system was about 260 liter.

The heat load calculated from Fig. 7 was about 83 W. In this case, the horizontal current lead was located above the liquid nitrogen. Therefore, the joule heat loss induced by the horizontal current lead was not the load of GM cryocooler. But in case of the horizontal current lead was immersed in liquid nitrogen, the heat loss was measured as about 108 W. Consequently, the heat loss induced from the current lead was most dominant factor to decide the total heat load of cryogenic system.

6. CONCLUSIONS

In this investigation, the sub-cooled nitrogen cooling system of 6.6 kV/200 A inductive SFCL for short circuit test was developed. The principles and methods of fabricating the cryogenic system were introduced in this paper. We found that the location of horizontal current lead is the dominant factor to decide the amount of total heat load and introduced how to reduce the amount of sub-cooled nitrogen by using dummy bobbin. And the decompressing method by using the rotary pump at the initial cooling is proved very efficient through experimental results. The temperatures of DC reactor in sub-cooled nitrogen were almost similar to each value measured at several points. The proper pressure for sub-cooled nitrogen state could be achieved by injecting the helium gas into the cryogenic system because of its very low freezing point. This sub-cooled nitrogen system was developed only for the short run operation test. In next 3rd year research (2003~2004), the sub-cooled nitrogen cryogenic system for field test will be developed.

ACKNOWLEDGMENT

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