Design and Cooling Characteristic Results of Cryogenic System for 6.6 kV/200 A Inductive Fault Current Limiter

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***Abstract*—The conduction-cooled cryogenic cooling system for 1.2 kV/80 A inductive Superconducting Fault Current Limiter (SFCL) was fabricated and tested for its cooling characteristics in 2002. The observed thermal stability of the conduction-cooled system was very unreliable and precarious for the applied superconducting equipment with very large variation of currents like SFCL. Therefore, we replaced the conduction-cooled system with the sub-cooled nitrogen system for the 6.6 kV/200 A SFCL.**

In this paper, the design techniques and test results of cooling characteristics were introduced. The conditions for achieving the sub-cooled nitrogen state were 1 atm and 64 K. First, the temperature of 64 K was achieved by using the rotary pump and then the pressure of 1 atm was achieved by GHe. The characteristics of liquid nitrogen were strongly enhanced in these conditions. This fabricated cryogenic system merely for the short run operation test SFCL. Finally, the cryogenic system for the long run operation test SFCL was introduced.

***Index Terms*—Cooling system, inductive SFCL, SFCL, sub-cooled nitrogen.**

I. INTRODUCTION

THE inductive SFCL is planned to be commercialized in Republic of Korea until 2011. This project is called 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea. The targets of this project are to develop the 6.6 kV/200 A SFCL in first phase, 22.9 kV/600 A, power distribution class SFCL in second phase, and 154 kV/2 kA, power transmission class SFCL in third phase. The 1.2 kV/80 A SFCL was developed at first year in first phase. The conduction-cooled cryogenic cooling method was adopted for the DC reactor of the 1.2 kV/80 A SFCL at first year in first phase. But the thermal stability of the conduction-cooled system for the DC reactor was very instable and not dependable [1], [2]. Therefore, the cooling type was changed to the sub-cooled nitrogen type system from the conduction-cooled type system. In this paper, the design and the experimental thermal characteristics of the sub-cooled nitrogen cooling system for DC reactor of 6.6 kV/200 A inductive SFCL were described.

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TABLE I
CHARACTERISTICS OF HTS TAPES

	Non-Reinforced	Reinforced
Thickness	0.21 mm	0.305 mm
Width	4.1 mm	4.1 mm
Critical Tensile Stress	65 MPa	265 MPa
Critical Tensile Strain	0.15%	0.4%
Critical Bending Diameter	100 mm	70 mm
Critical Current @ 77 K	115 A	115 A

II. DC REACTOR OF 6.6 kV/200 A INDUCTIVE SFCL

A. Characteristics of Superconducting Tape

High-T_c superconducting (HTS) tapes used in this research was manufactured by the American Superconductor Corporation (AMSC) and two kinds of HTS tape were utilized for making the DC reactor. The first one is the nonreinforced tape and the second one is reinforced tape.

1) Non-Reinforced Tape: The characteristics of HTS tapes were compared in Table I. The DC reactor of 6.6 kV/200 A inductive SFCL is composed of five bobbins connected in series. Each bobbin was connected by the copper blocks. Therefore, the heat loss would be generated in these copper block parts and they would be the heat load of the cooling system. The heat generated loss in these parts could be minimized by attaching the HTS tapes to the copper blocks. The nonreinforced tape was used as the auxiliary tape because the resistance of nonreinforced tape is lower than the resistance of reinforced tape. The V-I characteristics of the copper block with the auxiliary HTS tape and without the auxiliary HTS tape were tested. Consequently, the resistance of the copper block with auxiliary HTS tape was largely reduced compared with the copper block without auxiliary HTS tape.

2) Reinforced Tape: The mechanical characteristics of the reinforced tape are superior to the nonreinforced tape because the both sides of the reinforced tape are enhanced by thin SUS 315L tapes. The five bobbins were wound with the reinforced tape because of its very robust mechanical characteristics. The five bobbins could be wound with ease by using the winding machine for solenoid magnet developed by Yonsei University.

TABLE II
PARAMETERS FOR DESIGNING AND FABRICATING DC REACTOR

Num. of Bobbin	Dia. (mm)	Turns	Inductance (mH)	Length (km)
Design				
1	600	106	Total 103.8	0.80
2	640	99		1.60
3	680	93		2.40
4	720	88		3.20
5	760	83		4.00
Fabrication				
Num. of Bobbin	Dia. (mm)	Turns	Inductance (mH)	Length (km)
1	600	93	Total 84	0.72
2	640	88		1.44
3	680	83		2.16
4	720	78		2.88
5	760	73		3.60

B. Fabrication of the DC Reactor

The moderate inductance of DC reactor for 6.6 kV/200 A inductive SFCL was calculated as about 100 mH and the DC reactor consists of five bobbins which were connected in series and each bobbin was wound with four stacked reinforced tapes. The piece length of the reinforced tape was 200 m, so we designed the length of each five solenoidal magnet as 200 m. Therefore, the total estimated required length to fabricate the five solenoidal magnets was about 4 km.

But actually, the actual length of the DC reactor was about 3.6 km. The parameters for designing and fabricating the DC reactor were compared in Table II. The measured inductance of the DC reactor was about 84 mH because the total length of HTS tape was reduced. The total amount of liquid nitrogen was reduced by inserting the dummy bobbin into the center of the DC reactor. The reduction of the amount of liquid nitrogen means that the practical diminution of total heat loads of cryocooler. Actually, about 100 liter of liquid nitrogen was reduced by using the dummy bobbin which was made of GFRP.

III. THE SUB-COOLED NITROGEN COOLING SYSTEM

A. Design and Fabrication of Sub-Cooled Nitrogen Cooling System

The characteristics like thermal conductivity, critical current, and electrical insulation of HTS tape in the sub-cooled nitrogen are superior to the characteristics of HTS tape in the saturated liquid nitrogen. The conditions for achieving the sub-cooled nitrogen state were decided as 1 atm and 64 K [3]–[5].The schematic drawing of the cooling system and the location of the temperature sensors were shown in Fig. 1. The total heat load of this sub-cooled nitrogen cooling system was calculated as 87 W. The temperature sensors were numbered from 1 to 4 and shown in Fig. 1.

B. Experimental Results

The conduction heat loss generated by the current leads should be the main factor to determine the total heat load in this system. The cooling test was performed with two experimental conditions. The first condition was the level of liquid nitrogen was above the horizontal current lead (condition 1) and the second one was the level of liquid nitrogen was below the horizontal current lead (condition 2). The variations of temperature with time were shown in Fig. 2 and the sequences of cryo-cooling were represented in Table III. In these two experimental results, it was shown that the cooling time could be shortened by decompressing with rotary pump. The total

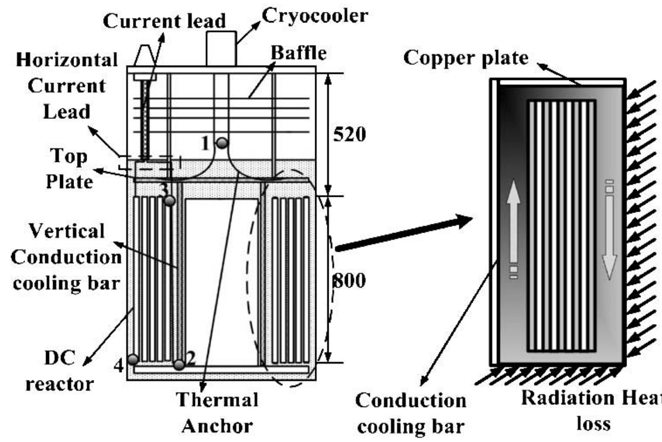

Fig. 1. Schematic drawing of the cooling system and location of temperature sensors.

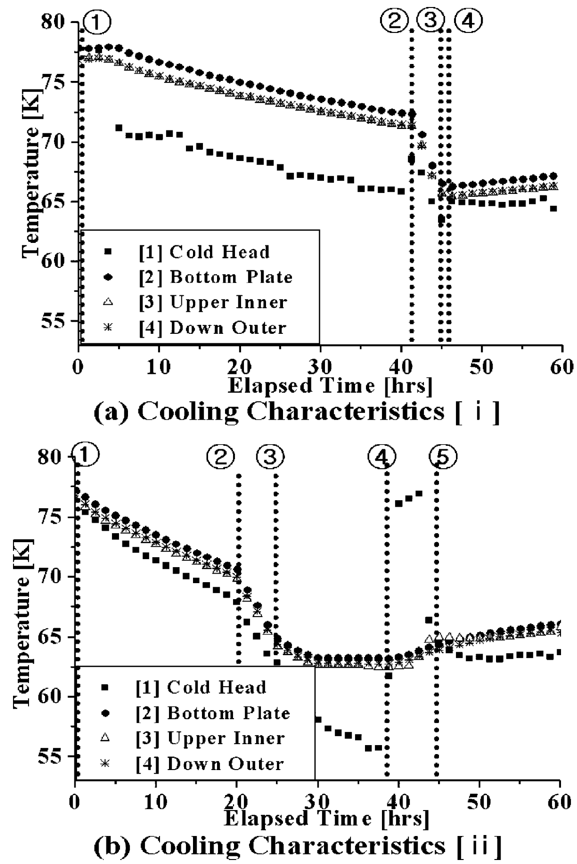

Fig. 2. Cooling characteristics of the sub-cooled nitrogen system w.r.t. the location of horizontal current lead. (a) Cooling characteristics [I]: observed result in condition 1; (b) Cooling characteristics [II]: observed result in condition 2.

TABLE III
SEQUENCE OF ACHIEVING SUB-COOLED NITROGEN STATE

Sequence	Operation	Date
Condition 1		
①	Turn on GM cryocooler	06/17/2003, 23:55
②	Turn on rotary pump	06/19/2003, 17:00
③	Turn off rotary pump	06/19/2003, 22:20
④	Inject gas helium	06/19/2003, 22:20
Condition 2		
①	Turn on GM cryocooler	06/23/2003, 13:30
②	Turn on rotary pump	06/24/2003, 09:30
③	Turn off rotary pump	06/25/2003, 02:20
④	Turn off GM cryocooler	06/25/2003, 16:00
⑤	Turn on GM cryocooler Inject gas helium	06/25/2003, 21:00

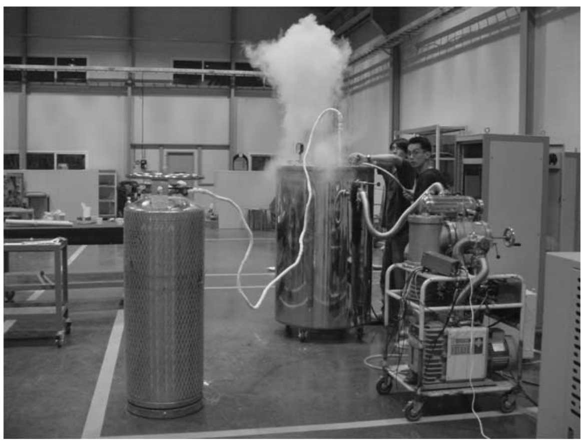

Fig. 3. Test of cooling characteristics of sub-cooled nitrogen system for 6.6 kV/200 A inductive SFCL.

heat load could be calculated from the characteristics between ① and ② in Fig. 2 and (1):

$$Q_L = C_p \cdot \rho \cdot V \cdot \Delta T \tag{1}$$

where, C_p is the specific heat, ρ is the density, ΔT is the difference of temperature, and V is the volume of the sub-cooled nitrogen, respectively. The value of specific heat is 2,000 $[\mathrm{J/kg \cdot K}]$, density is 860 $[\mathrm{kg/m^3}]$, ΔT is 13 K, and the volume of nitrogen was about 0.285 $\mathrm{m^3}$ in condition 1 and 0.260 $\mathrm{m^3}$ in condition 2, respectively. The measured heat load in condition 1 was about 107 W and the measured heat load in condition 2 was about 83 W. The temperature of saturated liquid nitrogen would be cooled down to 64 K by using only GM-cryocooler within 128 hours and 40 hours in condition 1 and condition 2, respectively. But the total cooling time could be shortened largely by using the GM-cryocooler and rotary pump. The general view of experiment was shown in Fig. 3.

IV. Discussion and Conclusion

The sub-cooled nitrogen cooling system was achieved with ease in last year research (2002∼2003). The difference of heat load between the cooling system at condition 1 and condition 2 was about 24 W. This difference of heat load was mainly occurred by the heat generation from the horizontal current leads.

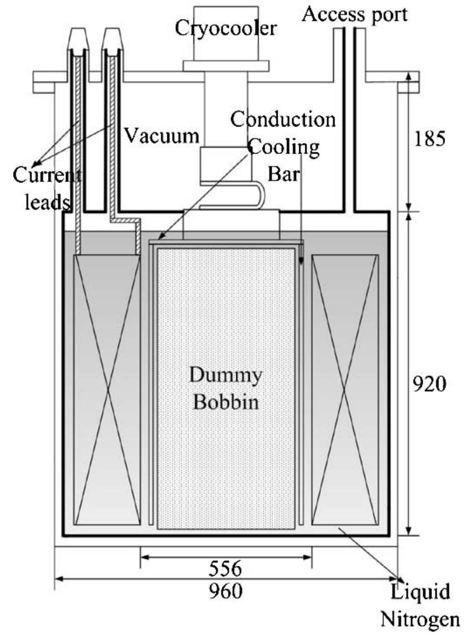

Fig. 4. Schematic drawing of cryogenic system for DC reactor of 6.6 kV/200 A inductive SFCL in 3rd year research.

To minimize the total heat load of the GM-cryocooler, the horizontal current lead should be located above the liquid nitrogen. In this experiment, we could know that the current leads should be the dominant factor to determine the total heat load of the cooling system. Therefore, the location of the current leads is very important factor to determine the efficiency of the cooling system.

The liquid nitrogen was frozen (between ③ and ④ region in Fig. 2(b) in decompressing state. The freezing of nitrogen could be prevented by injecting the GHe into the cryogenic system. The GHe, noncondensable gas is most profitable gas to compress the cryogenic system up to 1 atm because of its very low freezing temperature. Any other condensable gas is not proper for injection gas because the condensation process would cause the drop of pressure and increase of heat load in the cryogenic system.

The cooling time to cool down the temperature of the liquid nitrogen to 64 K will take about 128 hours and 40 hours in condition 1 and condition 2, respectively. The decompressing work with cryocooler and rotary pump howlingly not only shorten the cooling time but also remove the any other gas like water vapor, CO_2, and O_2 and other impurities.

V. Future Work

The cooling system was developed in the second year research for performing the just short run operation test like short circuit test and we could confirm the feasibility of the sub-cooled nitrogen cooling system for DC reactor of inductive SFCL through this investigation. The experimental results of the short circuit test will be described in another paper. The cooling system will be developed in the 3rd year research is for long run operation test. Therefore, the cooling system should be the vacuum system to minimize the amount of heat loss. The schematic drawing of cooling system is shown in Fig. 4.

Moreover, many other problems like the temperature control system, the liquid nitrogen filling system, and the method of detecting the level of liquid nitrogen are should be studied.

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