

Development and Test of a Cooling System for a 154 kV Superconducting Fault Current Limiter

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Abstract

The superconducting fault current limiter (SFCL) is an electric power device that limits the fault current immediately in a power grid. Korea Electric Power Corporation (KEPCO) has been developing a 154 kV, 2 kA SFCL since 2011 to protect power grids from increasing fault current and improve the stability and quality of electric power. This SFCL adopts 2G YBCO wires and operates at 71 K and 5 bars. In this paper, a cooling system for the 154 kV SFCL and its cooling test results are reported. This cooling system uses a Stirling-type cooler to make sub-cooled liquid nitrogen (LN₂), which cools the superconductor modules of the SFCL. The LN₂ is circulated between the cooler and the cryostat that contains superconductor modules. The LN₂ also plays the role of a high voltage insulator between the modules and the cryostat, so the pressure was maintained at 5 bars for high insulation performance. After installation in a test site, the cooling characteristics of the system were tested. In this operation test, some important data were measured such as temperature distribution in LN₂, pressure change, performance of the heat exchanger, and cooling capacity of the total system. Consequently, the results indicate that the cooling system operates well as designed.

Keywords: superconducting fault current limiter, cooling system, test operation, liquid nitrogen, YBCO

I. INTRODUCTION

In Korea, increasing power demand is leading to increased electric power utilities and highly interconnected systems. Consequently, fault current is exceeding the capacity of current circuit breakers. Korea Electric Power Corporation (KEPCO) has taken several measures such as splitting buses or lines, adopting the current limiting reactor and so on, but these have intrinsic problems such as high cost, power loss during normal operation or reduced reliability. Otherwise, a Superconducting Fault Current Limiter (SFCL) seems like the best option [1]. An SFCL, having no impedance during normal operation, is a power device that can limit the fault current immediately.

KEPCO developed a 22.9 kV, 630 A hybrid type SFCL, and it had been successfully operated in a real grid [2][3]. Due to higher demand at the transmission level, a 154 kV, 2 kA SFCL has been developed since 2011. This SFCL is resistive type so it uses the quenching phenomena to limit the fault current. It uses High Temperature Superconductors (HTS), in detail, 2G YBCO tapes, 12 mm width, and SUS stabilized. The cooling system of the SFCL should use Liquid Nitrogen (LN₂) to preserve the Fault Current Limiting (FCL) modules from a large amount of heat that can be produced in an instant during a fault.

The normal operation pressure and temperature of the LN₂ that contains FCL modules were determined to be at 5 bars and 71 K, being a sub-cooled condition. It is known that lower temperature and higher pressure of LN₂ ensure high current density of YBCO tapes and good dielectric performances of LN₂ respectively [4]. Especially in highly sub-cooled LN₂, bubble generation owing to quenching can be suppressed [5] and easily re-liquefied into LN₂. Therefore the size of the cooling system can be minimized under largely sub-cooled condition.

The cooling system which can achieve the given operation condition, was designed and installed at a KEPCO power testing center. A brief summary of the system is introduced in this paper. Before the FCL modules and other electrical parts are finally assembled in the cooling system, the cooling performance should be verified. First of all, temperature distribution inside the main cryostat that contains FCL modules should be uniform. Unless the temperature is uniform, FCL modules can have too divergent critical current and thus are more vulnerable to local quenching. Also, the pressure of a sub-cooled LN₂ should be stably controlled despite continuous re-liquefaction over a liquid surface. In this work, the performances of the cooling system based on above criterions are demonstrated with its operation data.

II. DESIGN AND CONSTRUCTION ON SITE

The basic structure of the cooling system was designed as in Fig. 1. There are four major components: the main tank, the pressure builder, the sub-cooling cryostat and the cooler. The main tank is a cryostat that contains the FCL modules and is connected to other power devices. The sub-cooling cryostat is directly connected to the cooler and charging a saturated LN₂. The LN₂ cooling the FCL modules is circulated between the main tank and the sub-cooling cryostat by a cryogenic pump. The pressure builder builds and maintains the appropriate pressure of the main tank and circulated LN₂ by boiling LN₂ with a heater and venting valves. These cryostats were connected with vacuum jacketed pipes and valves.

A. Design

This cooling system uses a 4 kW cooler (Stirling cryogenics

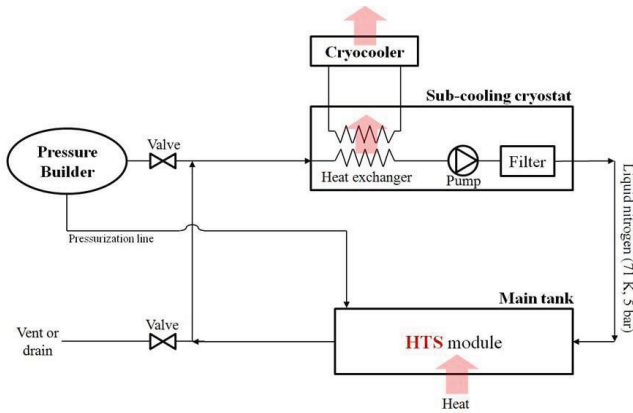


Fig. 1. Schematic diagram of the cooling system

Table 1. Design parameters of the heat exchange

Item	Value	Note
Inlet temperature	71.0 K	Return from the main tank
Outlet temperature	67.0 K	Supply to the main tank
Bath temperature	66.0 K	Surround temperature
Mass flow rate	0.5 kg/s	~ 35 lpm
Convection heat transfer coefficient	385.5 W/m ² K	Inside the pipe
Inner pressure	5 bar (G)	Same as the main tank

Table 2. Specifications of the cooling system for 154 kV SFCL

Item	Value	Note
The gross area	74 m ²	-
Cooling capacity	3.4 kW at 71 K	at 71 K (cold-head of the cooler)
Heat load	800 W	calculated
Power consumption	75 kW	cooler 48 kW, chiller 18.2 kW
Coolant	LN ₂	
Total LN ₂ weight	23 ton	
Operation condition	5 bar (G), 71 K	
Minimum maintenance period	6,000 hours	cleaning the regenerator of the cooler

BV. SCP-04 RL) and an appropriate heat exchanger and an LN₂ pump were needed. Fig. 2 shows the cooling capacity of the cooler, which was measured on site. As shown in Fig. 2(b), the cooling capacity of the cooler can be automatically controlled by changing the motor speed and the pressure of gas helium within 100~36 %. Based on this cooling performance, design parameters of the heat exchanger were calculated as in Table 1. The shape of the heat exchanger was assumed to be a circular tube. As an LN₂ pump, Barber & Nichols BNCP-64C, was chosen because of its large flow capacity

The main tank, a large horizontal cylindrical cryostat, contains the FCL modules which will be powered to 100 kVrms. Thus, the inside structure of the main tank should be designed considering the electric field distribution. The dielectric strength of nitrogen, 4 kV/mm, was also considered to decide the distances between the wall of the tank and the FCL modules. The distances determine the size of the main tank. The inner diameter of the tank is 3,180 mm, and the length is 5,720 mm. The volume inside

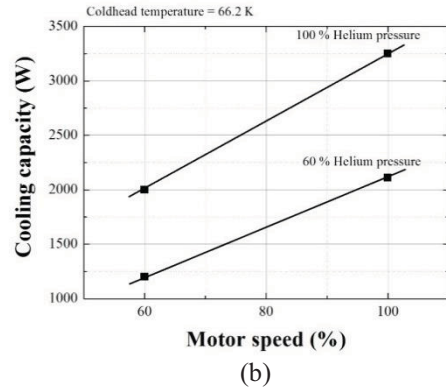
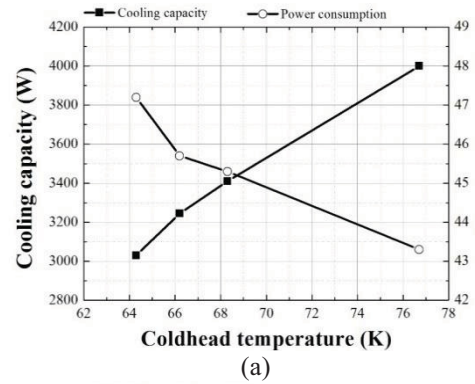


Fig. 2. Measured cooling capacity of the cooler. (a) Cooling capacity vs. cold-head temperature. (b) Cooling capacity at 66.2 K vs. motor speed and helium pressure

the tank is 29,000 L, and it should be charged with LN₂ at 90% of its level.

The main tank and other components containing LN₂ cooling the FCL should endure high pressure due to quenching. In this SFCL, the total heat generation is expected about 2.3 million joules. So the main tank was designed with the maximum pressure, 10 bar (G). It would also have appropriate rupture disks for safety.

B. Construction on site

The prototype SFCL was constructed at the KEPCO power testing center. The main tank was installed outdoors, and other parts were installed indoors. Fig. 3 shows the constructed system.

All metal parts were grounded, and dielectric adaptors were inserted between the LN₂ circulation pipes so that the main tank and others were electrically separated. Each component underwent inspection tests including a hydrostatic test, a gas leak test, and a trial operation. Specifications of this cooling system are summarized at Table 2.

III. COOL-DOWN TEST

After the construction, cooling tests were performed to confirm cooling performance and operation stability. Before being filled with LN₂, all cryostats were pre-cooled to prevent mechanical damages by thermal stresses. For temperature measurement, a silicon diode temperature sensor (Lakeshore DT-670-SD) was attached inside the sub-cooling cryostat, the pressure builder and on the surface of LN₂ circulating pipes. The pressure and level of each cryostat and LN₂ mass flow rate were also monitored during the test.



Fig. 3. The cooling system constructed at the site

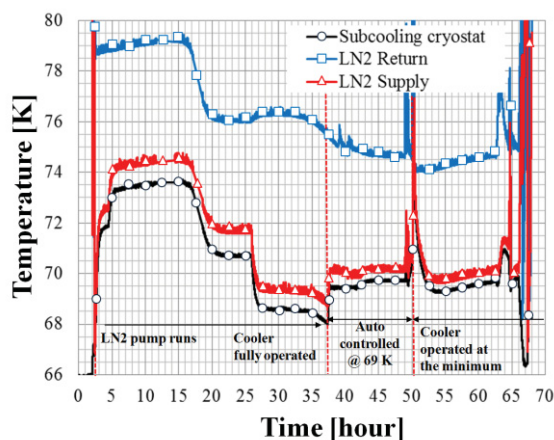
The test had been carried according to the following procedure: pre-cooling, filling LN₂, starting the cooler operation, circulating LN₂ by the pump and adjusting the set point temperature of the cooler.

A. Preliminary test

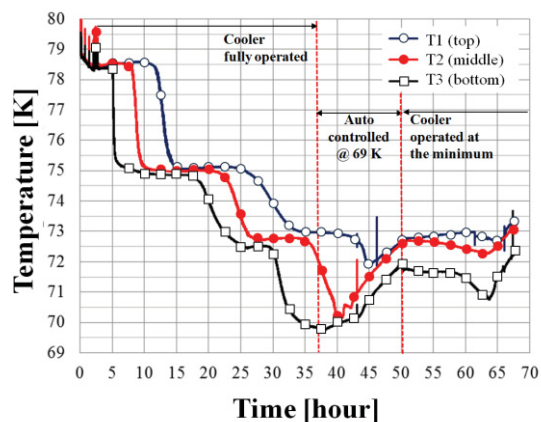
Once bushings and the FCL modules are installed, it is impossible to put any sensors inside the main tank. So in the first test, a cooling test without modules was performed to measure the temperatures inside the main tank. Three silicon diode temperature sensors were respectively installed at 834 mm, 1,349 mm, and 1,841 mm vertically from the bottom of the main tank. In this test, the heat invasion was expected to be smaller because current leads and the FCL modules were not included.

Fig. 4(a) shows the temperature change of the sensors, which are installed in a sub-cooling cryostat and on LN₂ pipes. Initially, the cooler was fully operated and then automatically controlled at 69 K for 13 hours. The temperature of the sub-cooling cryostat was successfully maintained by the cooler. The temperature difference between the LN₂ supply and return was decreased to less than 1 K. Fig. 4(b) shows the temperatures inside the main tank. The temperature trends are similar to those of the sub-cooling cryostat, but there are differences in the response time of three sensors respectively. The lower the height of the sensors, the earlier the temperature decreases. This is because the colder LN₂ from the sub-cooling cryostat is slowly piled up from the bottom. Once the supplied LN₂ reaches the return outlet, which is located at 80% of the main tank's height, the colder LN₂ can return to the sub-cooling cryostat and eventually the temperature of supplied LN₂ decreases. This phenomenon shows discrete temperature changes inside the main tank.

The temperature difference inside the main tank was less than 2 K at an auto-controlled region. Though this result may seem insufficient, this system can be expected to have better temperature uniformity. This is because what we monitored was in a transient state and the temperature differences were continuously being decreased.



(a)



(b)

Fig. 4. Results of the first test. (a) Temperatures of circulated LN₂ and bath. (b) Temperatures inside the main tank.

B. Test with the HTS modules

In the second test, the FCL modules were installed inside the tank with current leads and bushings. The LN₂ flow rate was about 28 kg/min during the test. Fig. 5 shows the results of the test. The temperatures of circulated LN₂ and the sub-cooling cryostat have a similar trend to that of the first test. The LN₂ supply and return temperature are much closer than the first test because the pipe position for LN₂ return in the main tank was changed from a 90% to an 80% level and colder LN₂ was drained to the heat exchanger. Also, the target temperature, 71 K, was stably obtained for 5 hours. Fig. 5(b) shows the pressure inside the main tank. Concurrently with the temperature controlled at 70 K, the pressure was also controlled at 5 bar (G), and it was successfully maintained by the pressure builder. During the test, the LN₂ level inside the main tank was also maintained, as shown in Fig. 5(b). So the FCL modules were able to be electrically tested and the cooling system operated well according to its purpose.

IV. SUMMARY

A cooling system for a 154 kV, 2 kA SFCL was developed and tested. It was designed to cool down and maintain LN₂ containing the FCL modules within 71 K, 5 bar (G). LN₂ was force-circulated between the main tank with modules and the sub-

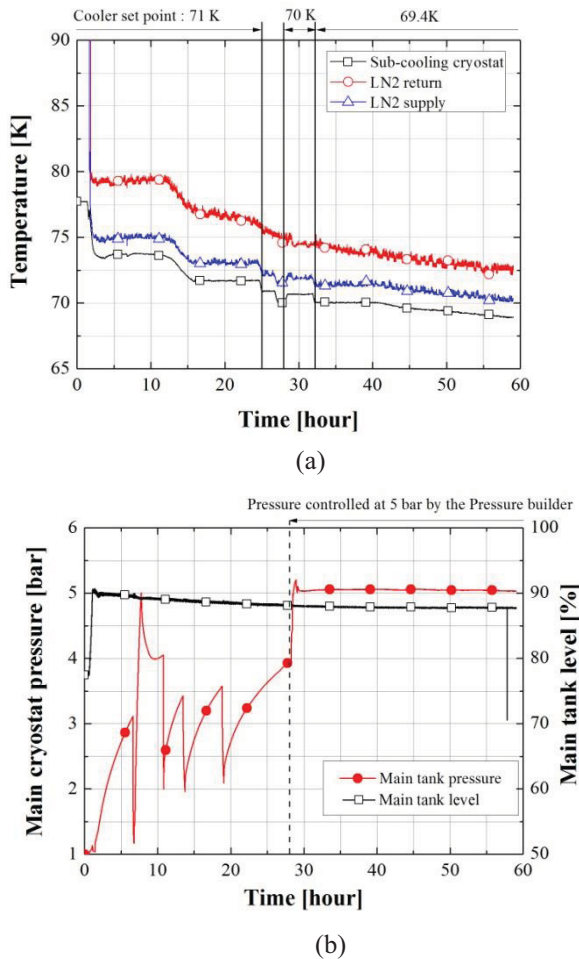


Fig. 5. The results of the second test. (a) Temperatures of circulated LN₂ and bath. (b) Pressure and level of LN₂ in the main tank.

cooling cryostat connected to the cooler by a pump. Also the pressure inside the tank and the circulating line is controlled at 5 bar (G) by the pressure builder. This system was constructed at the KEPCO power testing center. After the inspection for each component was completed, cooling tests for the entire cooling

system were conducted.

In the first test, the LN₂ temperatures inside the main tank were monitored without the FCL modules. Because the flow rate of circulated LN₂ was relatively smaller than the mass of LN₂ inside the main tank, the supplied LN₂ seemed to pile up from the bottom slowly. The temperature uniformity inside the main tank was less than 2 K. The cooler also operated well during the test.

In the second test, a similar test was performed with the FCL modules. The performance of the pressure builder was also tested and it controlled the main tank pressure smoothly. The cooling system obtained appropriate temperature and pressure so the FCL modules were able to be tested successfully.

ACKNOWLEDGEMENT

This work was supported by a grant from the Power Generation & Electricity Delivery Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by the Korean Ministry of Trade, Industry, and Energy.

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