Performance test of the cryogenic cooling system for the superconducting fault current limiter

Yong-Ju Hong\textsuperscript{1}, Sehwan In\textsuperscript{1}, Han-Kil Yeom\textsuperscript{1}, Heesun Kim\textsuperscript{2} and Hye-Rim Kim\textsuperscript{2}

\textsuperscript{1} Korea Institute of Machinery & Materials, Daejeon, 305-343, Korea
\textsuperscript{2} KEPCO Research Institute, Daejeon, 305-760, Korea

yjhong@kimm.re.kr

Abstract. A Superconducting Fault Current Limiter is an electric power device which limits the fault current immediately in a power grid. The SFCL must be cooled to below the critical temperature of high temperature superconductor modules. In general, they are submerged in sub-cooled liquid nitrogen for their stable thermal characteristics. To cool and maintain the target temperature and pressure of the sub-cooled liquid nitrogen, the cryogenic cooling system should be designed well with a cryocooler and coolant circulation devices. The pressure of the cryostat for the SFCL should be pressurized to suppress the generation of nitrogen bubbles in quench mode of the SFCL. In this study, we tested the performance of the cooling system for the prototype 154 kV SFCL, which consist of a Stirling cryocooler, a subcooling cryostat, a pressure builder and a main cryostat for the SFCL module, to verify the design of the cooling system and the electric performance of the SFCL. The normal operation condition of the main cryostat is 71 K and 500 kPa. This paper presents tests results of the overall cooling system.

1. Introduction

With progresses of superconducting technologies and developments of large scale power grid, superconducting fault current limiter (SFCL) will take place as a new alternative in fault current limiting technology in electric power system [1].

The SFCL is a device that limits quickly the fault current by using the impedance characteristics of the superconductor in normal operation condition. A large amount of heat is generated by outbreak of the fault current in the SFCL. A cryogenic cooling of the SFCL is an essential prerequisite to safely protect superconducting elements from the heat generation and to promptly recover them to normal operation condition.

When the fault current occurs, the heat is generated in a short time but the amount is very large. Cryocoolers cannot remove the heat generated within the recovery time required by the power grid. Consequently, liquid cooling using subcooled LN\textsubscript{2} is widely used for the cryogenic cooling of the SFCL.

Cooling superconducting elements in subcooled LN\textsubscript{2} at below 77 K and elevated pressure is a good choice in many respects. The critical current of the SFCL is increased at low temperature, so the size of the superconducting elements and the cryogenic system can be reduced. The heat dissipation during the fault current-limiting process generates bubbles by vaporization of the liquid nitrogen, resulting in the deterioration of the electric insulation.
The use of the subcooled LN$_2$ at elevated pressure can suppress the generation of bubble and evade the occurrence of the cavitation in the cooling system [2-5].

Several cryogenic cooling systems have been successfully developed for the distribution class SFCL in the subcooled LN$_2$ [6-8].

In Korea, due to higher demand in a transmission level, 154 kV / 2 kA SFCL have been developed. The SFCL is resistive type and uses quench phenomena in HTS tapes to limit the fault current. The normal operation condition of the 154 kV SFCL is 71 K and 500 kPa. This paper reports the performance of the cooling system for the 154 kV class SFCL.

### 2. Cooling system configuration for 154 kV SFCL

The cooling system for the 154 kV single phase SFCL consists of a Main Cryostat (MC), a Subcooling Cryostat (SC), a Pressure builder (PB) and a cryocooler as shown in figure 1.

The MC is responsible for the cooling of the superconducting element below the critical temperature by removing the dissipated heat by the circulation of the subcooled LN$_2$. The volume of the MC is 30 m$^3$, and it was filled with approximately 23,000 kg of LN$_2$. The LN$_2$ is supplied from the bottom of the MC, and returned at the height of 85 % of the MC. So that LN$_2$ is to be filled at least the height of 85 % of the MC.

| Table 1. Specification of the cryogenic cooling system for the 154 kV SFCL. |
|---------------------------------------------------------------|
| **Cooling system component** | **Specification**                                      |
|-----------------------------|-------------------------------------------------------|
| Main cryostat (MC)          | 71 K (500 kPa), Heat load < 800 W                     |
| Coolant                     | Subcooled LN$_2$ (500 kPa, 71 K, 23 Ton)              |
| Pressure Builder (PB)       | Automatic pressure control (500 kPa), Heater (2 kW)   |
| Subcooling Cryostat (SC)    | LN$_2$ circulation pump (50 lpm, 5700 RPM, 450W) /    |
|                             | Hydrocyclone ($50 \mu m$) / Heat exchanger (4 kW)     |
| Cryocooler                  | Stirling cryocooler, RL type (4.0kW@77K/48kWmax)       |
The SC, which is consisting of a heat exchanger, a hydro cyclone and a LN\textsubscript{2} circulation pump, is responsible for the subcooling of the LN\textsubscript{2}. The hydrocyclone is used to filter out particles with diameter of 50 \( \mu \text{m} \) or more to prevent partial discharge under high electric voltage in the MC. The heat exchanger with the capacity of 4 kW and the LN\textsubscript{2} circulation pump (Barber-Nichols Inc., BNCP-64C), which are used to cool the LN\textsubscript{2} down to 71 K, were installed.

The PB is responsible for the maintaining the pressure of the MC at 500 kPa. It is automatically controlled by the set pressure using the 2 kW heater and the solenoid valve.

A Stirling cryocooler (Stirling Cryogenics, SPC-04) is responsible for the re-liquefaction of the evaporated nitrogen LN\textsubscript{2} due to the heat duty of the heat exchanger.

### 3. Performance of the cooling system for 154 kV SFCL

To demonstrate the performance of components of the MC, the PB, the SC and the cryocooler, component tests were performed \cite{9}. Then performance tests of the cooling system for the 154 kV SFCL were carried out. Cooling processes are composed of a purging process, a cleaning and precooling process, a LN\textsubscript{2} filling process, a subcooling process and a pressurizing process.

First, all of cryostats were purged with nitrogen gas to remove the impurities. Then, small amount of the LN\textsubscript{2} was filled to the cryostat for the precooling.

Figure 2 and 3 show temperature changes of the surface of the MC. To monitor the change of temperatures, five E-type thermocouples are attached to the surface of the MC. Attached locations (T1, T2, T3, T4, T5) are the top, the height of 90 \%, 80 \%, 12 \% of the MC and the bottom of MC, respectively. Figure 4 shows the level of the LN\textsubscript{2} in the MC and the PB. In the figure, a reference time (\( \tau = 14.6 \text{ hrs} \)) denotes a time to replace the whole subcooled LN\textsubscript{2} in the MC by the operation of the circulation pump.

In the experiment, a small portion of the MC was initially filled with the LN\textsubscript{2}, and the MC was to be cooled by the evaporation of the LN\textsubscript{2} during a certain amount of time. This process is to suppress the generation of excessive stress in the wall of the MC and electric bushings.

After the time of 5 \( \tau \), the residual LN\textsubscript{2} in the MC was discharged for the cleaning of the cryostat, and the MC was filled with the LN\textsubscript{2} up to the height of 90 \% of the MC. For thermal stabilization, the evaporated nitrogen was vented during about 1.0 \( \tau \), during that period the level of the LN\textsubscript{2} in the MC was decreased to the height of 81 \% of the MC. So, the MC was refilled up to the height of 90 \% of the MC. At the same time, the PB and the SC were filled with the LN\textsubscript{2}. And then the vent valve of the MC was closed, and the subcooling process was carried out by turning on the cryocooler and the LN\textsubscript{2} circulation pump.

![Figure 2. Temperature changes on the surface of the MC during the precooling process.](image)

![Figure 3. Temperature changes on the surface of the MC during the LN\textsubscript{2} filling and the subcooling process.](image)
Heat loads of the MC and the PB were measured as about 688 W and 34 W, respectively, by using boil-off calorimetry. The heat load of the LN$_2$ pipe estimated at about 15 W, this value was based on the typical value of the heat leak of vacuum insulated pipes [10].

During the cool-down, since the LN$_2$ was supplied to the bottom of the MC, the cooling was conducted sequentially in the order from bottom to top of the MC. As the temperature of the LN$_2$ was decreased, the level of the LN$_2$ in the MC was decreased. These phenomena come from the densification of the LN$_2$.

The subcooling process is a cooling process of LN$_2$ from temperature of the saturated liquid to the temperature of 71 K. Figure 5 shows temperatures of cryocooler, the saturated LN$_2$ in the PB, the supplying LN$_2$ to the MC and the returning LN$_2$ from the MC, respectively. Silicon Diode temperature sensors were installed on the inlet and outlet pipe, and in the LN$_2$ of the SC. From the estimated thermal masses of the MC, superconducting module and LN$_2$, cool-down time is estimated at about 2.26 $\tau$. In the experiment, the cool-down time was approximately 3 $\tau$. This difference is believed to be caused from the turn-down operation of the cryocooler during cool-down time.

As shown in Figure 5, the temperature difference at steady state between the cryocooler and the LN$_2$ in the SC was about 1 K, and the temperature of the LN$_2$ in the SC was over 70 K. But the calculated temperature from the vapor pressure was about 69.4 K. These results indicate that the temperature gradient in the LN$_2$ of the SC due to the heat dissipation from the immersed heat exchanger.
The temperature difference between the supplying and returning LN$_2$ of the MC was reduced to 1 K in the steady state. Therefore temperature variations of the LN$_2$ in the MC were determined to be maintained at less than 1 K without the operation of the SFCL. In normal operation of the 154 kV SFCL, since the heat dissipation by the superconducting element is very small, it is also expected that significant changes will not occur.

Figure 6 shows the heat duty based on the temperature difference between the supplying and returning LN$_2$. The heat duty of the cooling system was reduced to 880 W in steady state. This value was higher than the expected value of the heat loads. The heat load comes from the MC, the PB, the LN$_2$ pipe and the GN$_2$ pipe. It is considered to have been mainly caused from the large heat load of the insufficient insulation of the GN$_2$ pipe. Hence, the heat load of the MC, the PB and the LN$_2$ pipe were 688 W, 34 W and 15 W respectively. The GN$_2$ pipe was the polyethylene foam insulated pipe.

Figure 7 shows the change of the pressure in the PB and the MC. The initial pressurization was carried out by the charging of the nitrogen gas to the gas space of the PB and the MC. Pressure control was achieved by the operation of the submerged 2 kW electric heater in the PB to evaporate the LN$_2$ and by the operation of the relief valve.

As shown in Figure 7, at the time of 10 $\tau$, the pressure of the MC and the PB approached to a set value of pressure. And then, during the period of $\tau$, the pressure was maintained to a set value without the operation of relief valve. As shown in Figure 4, continuous evaporations of the LN$_2$ in the PB resulted in the decrease of the level of the LN$_2$. So, at the time of 11$\tau$, it was carried out to supply the LN$_2$ from the MC to the PB until the level of LN$_2$ reached the level of 88%. At this time, there were no significant changes in the level of the LN$_2$ in the MC.
After the replenishment of the LN$_2$ in the PB and MC the pressure and the level of the LN$_2$ were slowly changing during the period of 6τ. Due to the evaporation of the LN$_2$ in the PB, the level of the LN$_2$ in the MC was gradually increased.

In conclusion, the LN$_2$ in the MC was maintained at the operation condition of 71 K, 500 kPa during more than 9τ.

4. Summary
In this study, we tested the performance of the cooling system for the prototype single phase 154 kV SFCL, which consist of the stirling cryocooler, the SC, the PB and the MC for the SFCL module, to verify the design of the cooling system and the cool-down procedure.

Cooling processes are composed of a purging process, a cleaning and precoring process, a LN$_2$ filling process, a subcooling process and a pressurizing process.

Results confirm that the cooling system and process are designed to ensure the normal operation condition of 71 K, 500 kPa. And temperature variations of the LN$_2$ in the MC are less than 1 K in normal operation.

Acknowledgements
This work was supported by the Power Generation and Electricity Delivery of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Science, ICT and Future Planning (No. 2011T100200043).

References
[1] Kraemer H et al 2012 Physics Procedia 36 921
[2] Nam K et al 2006 IEEE Transaction on Applied Superconductivity 16 727
[3] Nam K et al 2007 Cryogenics 47 442
[4] Ko J et al 2013 IEEE Transaction on Applied Superconductivity 23 5603204
[5] In S et al 2015 IEEE Transaction on Applied Superconductivity 25 3800204
[6] Ohtani Y et al 2004 IEEE Transaction on Applied Superconductivity 14 855
[7] Gong L H et al 2007 Cryogenics 47 450
[8] Maguire J F and Yuan J 2009 Physica C 469 874
[9] Yeom H et al 2014 Progress in Superconductivity and Cryogenics 16 66
[10] Flynn T 2005 Cryogenic Engineering (New York: Marcel Dekker) chapter 2 pp 70