Test results and analysis of cryogenic system for cooling HTS cables and the next stage plan

Fan Y-F.[1, 2], Gong L-H.[1], Xu X-D.[1], Li L-F.[1], Zhang L.[1], Xiao L-Y.[3]

[1] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100080, China
[2] Graduate School of Chinese Academy of Sciences, Beijing 100039, China
[3] Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100080, China

A 10-m long 10.5 kV / 1.5 kA three-phase alternating current high-temperature superconducting power cables prototype was developed and tested in China in August 2003. The sub-cooled liquid nitrogen was used to cool HTS cables and their terminations in this prototype. The cryogenic system comprised two parts: the sub-cooled liquid nitrogen cycle and the refrigeration station. Test results will be presented and analyzed in this paper. In addition, the next stage plan, which is the development of 75-m three-phase alternating current high-temperature superconducting power cables, will be installed in the power grid this year and tested the next year.

INTRODUCTION

In the past decade or so, the high temperature superconducting (HTS) power cable started to be developed and became the focus of research as one of the application of high temperature superconductor in the world [1,2]. In 2002, Pirelli Cables and Systems and Detroit Edison installed and operated the world's first HTS power cable to deliver electricity in a utility network. Its successful integration was a milestone in the process of HTS application and realized the transition of HTS cable technology from the laboratory to the real-world field [1]. In China, the research and development (R&D) project on HTS power cable was initiated at the end of 1997. In 1998, a 1-m long 1 kV / 1 kA HTS cable model was developed and successfully tested by the Institute of Electrical Engineering (IEE), CAS. Later, they studied a 6-m long 2 kV / 2 kA HTS power cable prototype to increase the critical current and to adopt the improved fabrication technique of HTS cable in 2000 [3]. Last year, collaborating with Technical Institute of Physics and Chemistry (TIPC), CAS, they successfully developed and tested a 10-m long 10.5 kV / 1.5 kA three-phase alternating current (AC) HTS power cables prototype.

With the development of HTS power cable, the cryogenic system for cooling HTS cables also won the chance of development. The cryogenic system of LN2 immersion was adopted in the 1-m and 6-m HTS power cable models. It was unfit for the longer and larger HTS power cable in the power grid, so the cryogenic system with high-efficiency and high-stability was needed for the real-world application of HTS power cable. We developed a cryogenic system for the 10-m HTS power cables prototype [4].

TEST RESULTS AND ANALYSIS

As of February 2004, the HTS power cables had been operated for 10 times. Duration of the operation at 1.5 kA was more than 5 hours each time. Meanwhile, the cryogenic system had been cumulatively

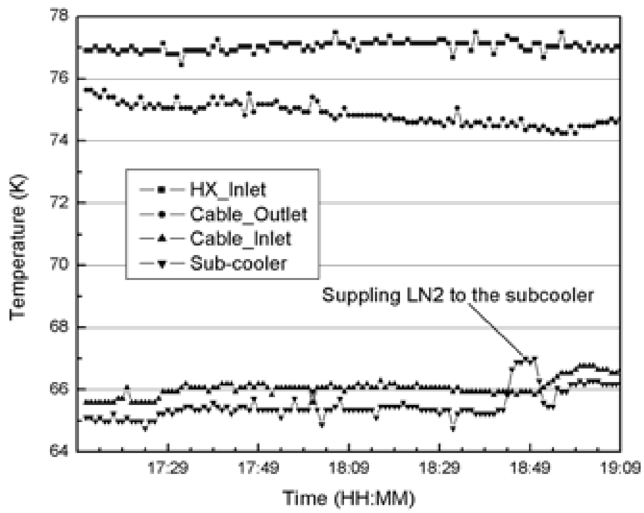

Figure 1　Temperature of LN2 during the running

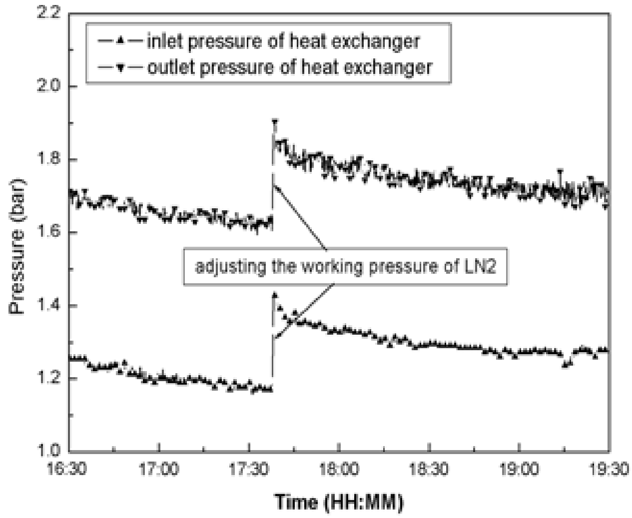

Figure 2　Pressure of LN2 during the running

worked for 80 hours. The test result, which was gotten on August 15, 2003, proved that the LN2 inlet and outlet temperatures of HTS cables were 65.5K and 75.5K respectively, when the LN2 flow rate was 800 L/h, and the fluctuation of the temperatures was about 1.0 K, as shown in Figure 1. Figure 2 showed the LN2 pressure distribution for the inlet and outlet pressure of heat exchanger inside the sub-cooler. In order to research the influence of electrical current on the heat load (corresponding to the cooling power) and LN2 consumption, we did a series of HTS cables tests under different electrical currents. The results were shown in Figure 3.

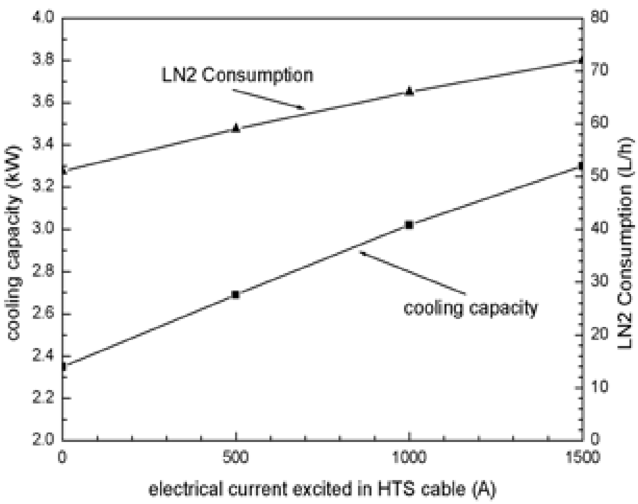

Figure 3　Influence of the electrical current

In January 2004, we carried out some experiments on cryogenic system to research the influence of LN2 flow rate and the inlet temperature of HTS power cables on the background heat load of whole HTS cable installation, including the cryogenic system. The background heat load means the heat load without electrical current passing the HTS cables. Figure 4 and Figure 5 respectively show the influences of LN2 flow rate on the temperature difference and pressure difference of the heat exchanger inside sub-cooler in the condition of different inlet temperatures. Seen from Figure 4, the temperature difference (ΔT) decreases as the flow rate increasing and the ratio of temperature difference to flow rate approximately keeps a negative constant. From the first principle of thermodynamics, the background heat load could be calculated by Equation 1, which follows:

$$Q = \dot{m} \cdot C_P \cdot \Delta T \tag{1}$$

with Q: heat load, $\dot{m}$: LN2 mass flow rate, C_P: LN2 heat capacity of constant pressure, ΔT: LN2 temperature difference of heat exchanger inside sub-cooler. The calculated value of heat load is about 2.35 kW. Also, Seen from Figure 5, the pressure difference (Δp) increases as the flow rate increasing and the ratio of them approximately keeps a positive constant.

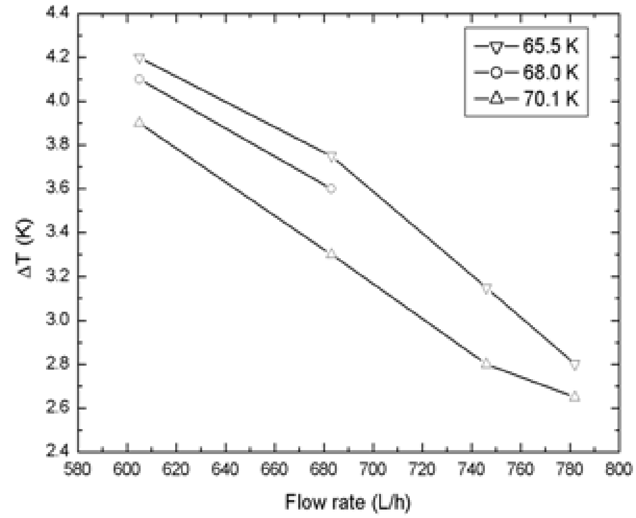

Figure 4 Influence of flow rate on ΔT

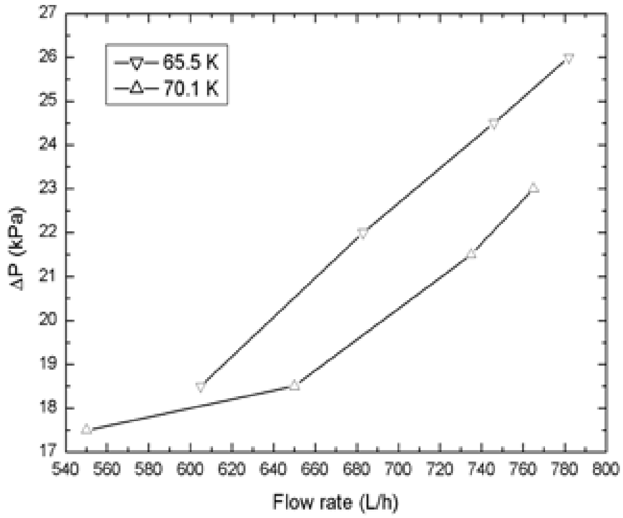

Figure 5 Influence of flow rate on Δp

As mentioned in above paragraph, test results have indicated that cryogenic system could have operated stably and reliably for cooling HTS power cables and have verified that both design and installation are correct and successful. Cryogenic system of using the sub-cooled LN2 cycle to cool the HTS power cables could satisfy the demand of the high-efficiency and high-stability for the real-world application of HTS power cable. Because of the special property of low boiling point to LN2, the trouble-free startup of LN2 pump using in a LN2 cycle provides the valuable experience for us. Additionally, a data acquisition and control system has been built, and heat load, LN2 flow rate, temperature, and pressure have also been measured correctly. All results provide confidence in the design approach of cryogenic system for 75-m HTS cables installation. On the other hand, the real background heat load is 2~3 times larger than that estimated theoretically. It may result from two main parts: conducting heat load of the LN2 feeding line and HTS cables terminations, and conducting heat load of the six current leads from room temperature. Perhaps use of the Super Insulated Vacuum (SIV) lines and optimization of the design and structure of current leads [5] could effectively reduce the heat load.

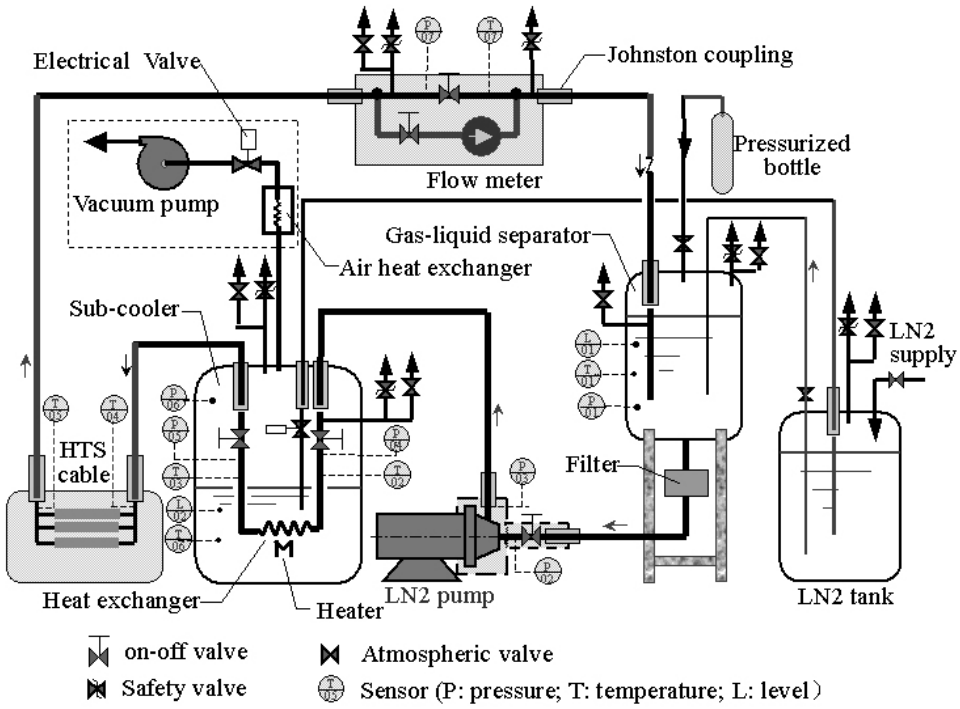

Figure 6 Simplified flow diagram of the cryogenic system for 75-m HTS cables installation

NEXT STAGE PLAN

Based on the 10-m HTS power cables prototype, we will develop the 75-m three-phase AC HTS power cables installation in the next two years. The 75-m HTS power cables installation will be developed together by IEE of CAS, TIPC of CAS and Gansu Changtong Cable Group. The cables will be installed and operated in the power grid in Baiyin, Gansu province. The project is being built now and will be finished at the year-end and tested the next spring. Similarly to the 10-m HTS power cables prototype, the cryogenic system for the 75-m HTS power cables adopts the sub-cooled LN2 cycle to cool the HTS cables and their terminations. It consists of two parts: the sub-cooled LN2 cycle and the refrigeration station. The simplified flow diagram is shown in Figure 6. The cooling capacity is produced by the method of decompressing LN2 in the sub-cooler to sub-atmosphere.

CONCLUSIONS

In this paper, we have presented the test results of the cryogenic system for cooling the 10-m HTS cables prototype. The results include the distribution for the temperature and pressure of LN2 during the HTS cables running, the influence of electrical currents on the heat load and LN2 consumption, and the influence of LN2 flow rate on the temperature difference and the pressure difference. Besides, some helpful experience has been summarized through results analysis and is the basis of design and manufacture of the cryogenic system for the 75-m HTS power cables. Finally, the next stage plan: development of the cryogenic system for the 75-m HTS power cables installation has been introduced.

ACKNOWLEDGEMENTS

This project is derived from The National High Technology Research and Development Program (Project No. 2002AA306161) and together supported by the Ministry of Science and Technology and Gansu Changtong Cable Group.

REFERENCES

1. Pietro Corsaro, Massimo Bechis, Paola Caracino, et al., Manufacturing and commissioning of 24 kV superconducting cable in Detroit. Physica C 378-381 (2002) 1168-1173
2. Takato Masuda, Takeshi Kato, Hiroyasu Yumura, et al., Experimental results of a 30 m, 3-core HTSC cable. Physica C 372-376 (2002) 1555-1559.
3. Y.B. Lin, L.Z. Lin, Z.Y. Gao, H.M. Wen, L. Xu, L. Shu, J. Li, L.Y. Xiao, L. Zhou, and G.S. Yuan. Development of HTS transmission power cable. IEEE Trans. on Applied Superconductivity (2001) 11 2371-2374
4. Y.F. Fan, L.H. Gong, X.D. Xu, L.F. Li, L. Zhang, L.Y. Xiao, Cryogenic system with the sub-cooled liquid nitrogen for cooling HTS power cable. Cryogenics (accepted)
5. J.M. Lock, Optimization of current leads into a cryostat. Cryogenics (1969) 9 438-442