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Design and Operational Test of 22.9kV, 30m, 3phase HTS Cable Cooling System

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***Abstract*-- The 30m, 3phase, 22.9kV HTS (High Temperature Superconducting) power cable system was produced by LS Cable Ltd. The project aims for a commercial HTS cable. The designing, the manufacturing and the initial operating of HTS cable system were completed by 2004. Then, we have performed a long term operational test since February, 2005. This paper mainly reports the result of the HTS cable cooling operation.**

1. INTRODUCTION

HTS (High Temperature Superconducting) power cable is a promising technology expected to be the solution of the growing electric power demand. [1] Nowadays, several projects of a commercial HTS power cable are in progress.

LS Cable Ltd. has developed the HTS power cable system since 2001. In 2003, the 22.9kV single-phase, 30 meter long HTS cable was successfully developed. In 2004, the 22.9kV 3-phase, 30 meter long HTS power cable was developed and the preliminary operational test was carried out. [2][3] Several problems were discovered and corrected in the preliminary operation. In 2005, the long term operational test was performed. Through those developments and tests, the design concepts for the real power grid were validated and the manufactured HTS cable systems were demonstrated.

A high temperature superconductor remains in the superconducting state only under its critical temperature. Consequently, to make HTS power cable remain in the superconducting state, it is supposed to be cooled due to the thermal invasion from outside and the heat generation by the applied current as well as the initial cooling heat load. [4]

For the cooling of the HTS cable, liquid nitrogen is circulated through the inner side of the cable cryostat. This method can remove the large amount of heat by the convective heat transfer between the HTS conductor surface and the circulated liquid (the coolant). [5]

There are mainly two available cooling methods of the coolant heated from the cable. One is using the cryo-coolers and the other is using the latent heat of the evacuated liquid nitrogen.

Before the 22.9kV, 30m, single-phase HTS power cable system was developed in 2003, the project had been in the early stage. So the latent heat method which is easier to achieve the research purposes was applied. But the latent heat method consume much of the liquid nitrogen consecutively. It is more desirable to use the cryo-coolers in the real power grid cooling system because it requires reliable and economical operation for a long period. The target of the project performed in 2004 is the commercial system for the real power grid. Therefore, the cryo-cooler was applied along with the existing evaporation cooling equipment. The cooling system was adjusted after the preliminary test in 2004. Then, the 6 month operational test was successfully performed in 2005.

The HTS cable cooling system requires following operational characteristics; the temperature control ability to maintain the superconducting state, the pressurizing ability to prevent the cavitations, and the operational control ability to manage accidents. This paper reports the design and the operational characteristics of the cooling system developed in 2004

2. DESIGN AND OPERATION TEST

2.1. The design of 3-phase 30m HTS cable cooling system

The thermal loads estimated by the design are described in Table 1. The total thermal load of the cooling system is designed to be 1100W under the application of AC 1260A. In the operation of HTS cable, the pressure of circulated liquid nitrogen is supposed to be maintained over 2.5bar to assure the electric insulation and prevent cavitations. The outlet temperature of the liquid nitrogen has to be

TABLE I
THERMAL DESIGN CONDITIONS OF HTS CABLE SYSTEM (AC 1260A)

Component	Load(Watt)
HTS cable (30m, 3phase)	140
Termination (6EA)	700
Split Box (2EA)	50
Cooling System	100
Transfer Line	100
Total Load	1090

maintained lower than 77K, the evaporation temperature under the atmospheric pressure for the stable operation.

The circulated liquid nitrogen is pressurized to be over 2.5bar by the circulating pump and cooled to be lower than 77K by the heat exchanger of cooling system. Especially, the heat exchanger installed on the cold head of cryo-cooler requires optimal shape design because it is restricted by the shape of the cold head as well as by cooling load and pressure drop. In this cooling system, the heat exchanger was designed to have 70% heat exchange efficiency and validated by analysis of 1-D and 3-D commercial simulation codes.

2.2. The assembling of 3-phase, 30m HTS cooling system

The 3-phase, 30m, 22.9kV HTS power cable developed in 2004 is composed of a HTS cable, two split boxes that splits each phases at the end of the cable, and six terminations that connect each phase with normal power cables. And the cooling system is composed of the cryo-cooler installed equipment, the evaporation cooling equipment using the latent heat of evacuated nitrogen, and the LN2 transferring super-insulated pipe lines.

The evaporation cooling equipment works for six terminations. And the cryo-cooler cooling equipment operates for the HTS cable and two split boxes. The cryostat of the HTS cable and two split boxes is separated from those of six terminations. The separation of the cryostats provides the benefits to minimize the risk of an accident and allow measuring the exact thermal loss of each part. Fig. 1 shows the diagram of the entire cable system.

The cooling method using the latent heat of evacuated nitrogen is hard to achieve an economical operation because of the continuous nitrogen consumption. The cooling method for the real power grid should have flexible and reliable cooling ability by using appropriate numbers of cryo-cooler. To design and validate the cooling equipment for real power grid, 1EA of GM type pulse tube cryo-cooler was applied.

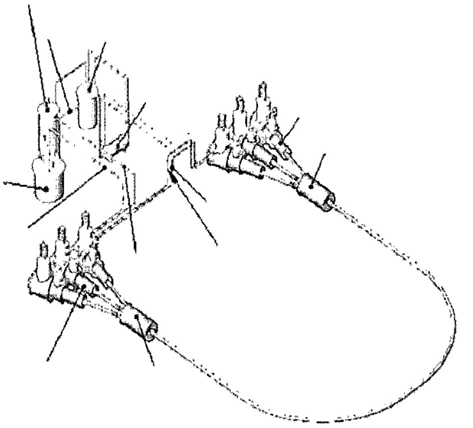

Fig. 1. 30m 3phase 22.9kV HTS Cable System.

The commercial cooling system for real power grid is intended to handle all thermal loads with cryo-coolers only. But the 1EA of cryo-cooler for operational test has the limit of thermal capacity. To achieve the operational test for the wide range of thermal load, the thermal exchange between two cooling equipments was allowed by installing a 500W class plate heat exchanger in the distribution box. Table 2. shows the summary of the component specifications in each cooling equipment.

TABLE II
COMPOSITION OF COOLING SYSTEM

Cooling Types	Capacity	Components
Cryogenic Cooler	350W (@74K)	1. Circulation Pump (1EA, 0.3kg/s@ ΔP=2.6bar) 2. Heat Exchanger (1EA, 70%) 3. All in One Cryostat
LN2 evaporation	3000W (@74K)	1. Circulation Pump (1EA, 0.4kg/s@ ΔP=2.6bar) 2. Heat Exchanger (1EA, 70%) 3. LN2 Evaporation Pump (2EA)

The cryostat of the cable was made of aluminum and formed into dual concentric corrugated pipe. The radiative heat transfer is reduced by MLI (multi-layered insulation) on the surface of inner corrugated pipe. There are three HTS cores inside the inner cable cryostat, so called '3-in-1' type. The HTS core consists of a flexible stainless steel former, a layer of HTS conductor tape, layers of electrical insulation, a layer of HTS shield tape, and layers of mechanical protection. In the cable, LN2 go through three formers and returns through the inner cryostat ('Go and return' type). The configuration of this HTS cable is shown in Fig. 2.

In the termination, the prominent thermal invasion breaks out at the current lead that connects the HTS conductors to the electric power facilities of normal temperature because of the direct exposure to the atmospheric temperature and high thermal conductivity of copper. So, computer simulation was performed in various conditions to find the optimal design of current lead.

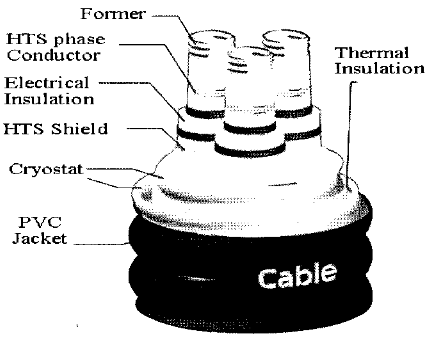

Fig. 2. HTS Cable Configuration.

2.3. Operation Control System of HTS Cable

Throughout the preliminary test, operating the whole HTS system required more than three engineers. And it was difficult to achieve a steady state by the manual operation. In the real power grid that need to have long distance cables and maintain the operating state for a long time, the manual operation will cause greater labor cost expansion and more unstable operation. Therefore, an automatic control method is utilized for a stable operation of the HTS system.

The automatic control system controls the cooling equipments and the electric devices coping with the various operating situations. Moreover it can remotely monitor all sorts of data and send the warning message about the outbreaks. Fig. 3 shows the monitoring and manipulating display of the operation control system. Table 3 shows the summary of the controlled variables and the control method.

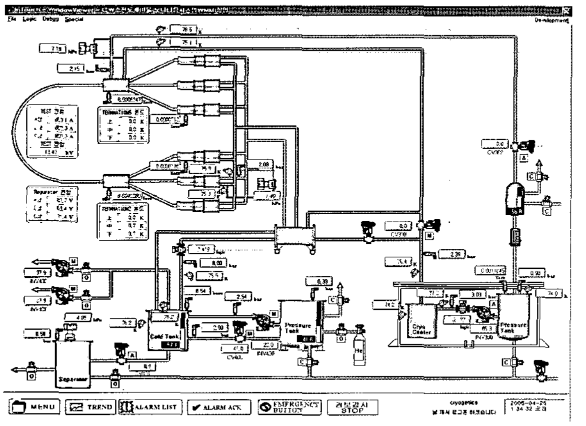

Fig. 3. Control System Panel of HTS Cable System.

TABLE III
CONTROL VARIABLES AND MANIPULATION METHOD OF SYSTEM.

Control Variables	Manipulation Method
LN2 mass flow rate	Hz of circulation pumps
LN2 outlet temperature (cable)	Heat change with LN2 evaporation
LN2 outlet temperature (termination)	Hz of evaporation pumps
LN2 outlet pressure	Openness of control valve
Level of LN2	Openness of sol. valve and control valve
Current/Voltage	regulator, CT

2.4. Long-term Operational Test

After adjusting the cooling system and establishing the operation control system, the long-term operational test was being carried out for six months. During the long-term test, the series of the operations ('cool-down', 'current transportation', and 'warm-up') were repeated 3 times.

The temperature and the pressure of the each component were stably maintained during the 'current transportation'. Fig. 4 shows the monitoring display.

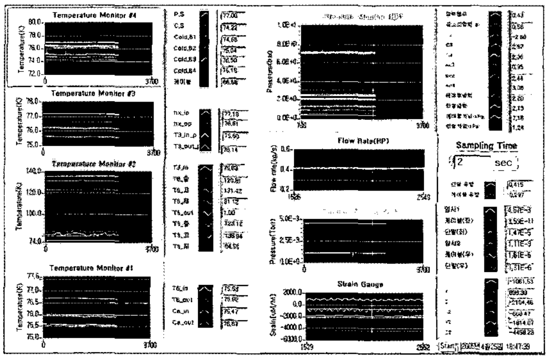

Fig. 4. Data Monitor of HTS Cable System.

2.5. Pressure Drop of the HTS Cable

Fig. 5 shows the measured data of the pressure loss in the cable. When the mass flow rate of LN2 is 0.25 kg/s, the pressure loss in the cable is about 5 kPa.

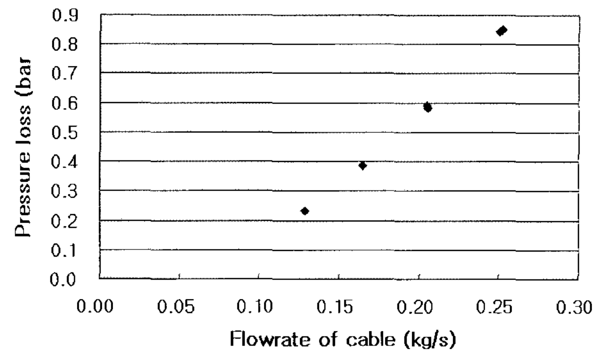

Fig. 5. Cable pressure loss.

The pressure loss of the cable is almost due to that of the former because the pressure loss of return flows is negligible. The pressure loss of the cable can be calculated by the friction factor of the former by using equation (1) below.

$$\frac{\Delta P}{\rho} = f\frac{L}{D}\frac{v^2}{2} \tag{1}$$

Fig. 6 shows the friction factor of the former as a function of Reynolds number. The friction factor of the former was calculated to 0.26 by the above equation. And it was 10% less than the estimated.

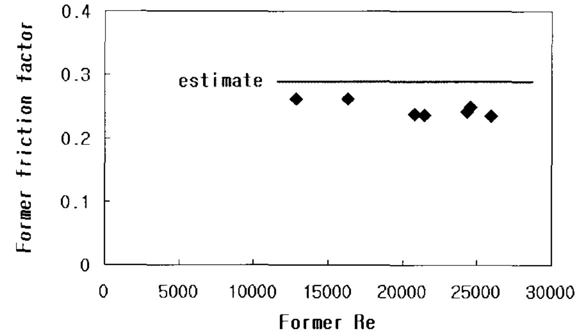

Fig. 6. Former friction factor.

The pressure loss of the terminations is not only very small but also unchanged even in the long distance cable.

2.6. Thermal Loss of the HTS Cable

The thermal loss through the cable insulation was calculated by the mass flow rate and the temperature increase between the inlet and the outlet as shown in equation (2) below.

$$\dot{Q} = \dot{m} C_p \Delta T \qquad (2)$$

The thermal loss of the cable cryostat was calculated to 3.5 W/m. It was somewhat higher value than the expected value of the cryostat design. It was because the thermal loss of the cable cryostat can be increased by several times in the bent part. [6] The HTS cable had the bent part which was 16 m long and had a radius of 5 m. We are now carrying out an individual experiment of thermal insulation to improve thermal performance.

3. CONCLUSION

The 22.9kV 30m long 3 core HTS power cable system was supplemented through the preliminary operation in 2004. Then, we successfully carried out the long-term operational test for about six months. The cooling system of the HTS cable stably operated when the electric current was transported. The data measured in the long-term operational test were utilized in the design and the manufacture of the HTS cable for real power grid.

The automatic operation control system that is required for the real power grid was established. Through the automatic control, the stable operational condition, the reduction of the operators and the preparation for the various situations were achieved.

The cooling equipment using the cryo-cooler was verified by applying to the HTS cable cooling system. Through the evaluation and the verification, the foundation of the cooling system using cryo-cooler is laid.

Also, the six-month operating experience of the HTS cable system gave us the practical know-how to maneuver and maintain the system.

The large thermal loss in the bent part of the cable is the subject to improve. The tests to promote the performance of the thermal insulation are now being carried out.

ACKNOWLEDGMENT

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