ARTICLE IN PRESS

Physica C xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Results of KEPCO HTS cable system tests and design of hybrid cryogenic system

J.H. Lim[a,*], S.H. Sohn[a], H.S. Yang[a], S.D. Hwang[a], D.L. Kim[b], H.S. Ryoo[c], H.O. Choi[c]

[a] *Korea Electric Power Research Institute, Korea Electric Power Corporation, Republic of Korea*
[b] *High Magnetic Field R&D Team, Korea Basic Science Institute, Republic of Korea*
[c] *Korea Electrotechnology Research Institute, Republic of Korea*

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
HTS cable system
Unbalanced load test
Hybrid cooling system

ABSTRACT

In order to investigate the compatibility as a power utility facility, Korea Electric Power Corporation (KEPCO) had installed a 22.9 kV, 1250 A, 100 m long high temperature superconducting (HTS) power cable system. Using the HTS cable, various tests have been performed to investigate electrical and thermo-mechanical properties. Since 2005, a series of thermal cycle tests between liquid nitrogen (LN_2) and ambient temperatures have been conducted using a vacuum-pump driven open-loop cryogenic system with a capacity of 3 kW. In the tests, although the open-loop cryogenic system was reliable to operate the HTS cable system, it was not effective in economic view point because LN_2 consumption was larger than expected. In order to secure against unexpected emergencies and solve the problem of LN_2 consumption, a hybrid cryogenic system was designed and installed. A stirling cryocooler was employed and combined with the open-loop cryogenic system. Considering the average heat load at rated condition, the cooling capacity of the cryocooler was determined to 4 kW at 77 K. In this paper, results of performance tests and the design of the hybrid cooling system are presented.

1. Introduction

To the aim of application of HTS cable to practical power grid, KEPCO had installed a 22.9 kV, 1250 A, 100 m long HTS power cable system and has carried out various tests. Since the HTS cable system was installed, rated voltage–current tests, over voltage tests, unbalanced load tests, and so forth have performed. As the results, reliability and feasibility on the application of HTS cable were convinced and the operation technique of HTS cable system was established [1–4]. For about four years, the HTS cable system has experienced eleven times of cooling-down and warming-up cycles. The tests were performed using an LN_2 decompression cooling system described in Fig. 1. The cooling system had a cooling capacity of 3 kW and the maximum flow rate of LN_2 was 50 L/min [5]. In this paper, we introduce the dependence of heat loss on thermal cycle test, cooling capacity verification, and unbalanced load test results.

On the other hand, in order to provide against unexpected situation such as system damage, a back-up system for the cooling system was prepared. A cryocooler of the back-up system, which was purchased from Stirling Cryogenics & Refrigeration BV in Netherlands, had a cooling capacity of 4 kW at 77 K. The hybrid cooling system composed of a decompression cooling system and a stirling cryocooler was designed and established. For the performance test of the cooling system, it could operate in three kinds of cooling loops; decompression mode, cryocooler mode, and hybrid mode. In this study, the results of the HTS cable performance test are presented and the design of hybrid cooling system is introduced.

2. Performance test results

2.1. Dependence of heat loss on thermal cycle test

Since the heat loss has influence on the efficiency of HTS cable operation seriously, it is necessary to investigate the variation of the heat loss according to the operation state of the cable. In HTS cable system, the heat transfer from outside and Joule heating in conductors can bring about heat loss. In particular, welding parts of cryostats can be a weak point to cause the heat loss. For investigating those effects during the HTS cable operation, we measured the changes of heat loss under the operation condition of 66.4 K and LN_2 flow rate of 40 L/min. The results are shown in Table 1. From 2nd to 9th thermal cycles, the heat loss of the HTS cable system was measured as 150 W, and the variation of cable cryostat part was 60 W. After the test, degradation of cryostat was not found during the system inspection. However, it was thought that the variations of heat loss were caused by seasonal changes because outside temperature was varied continuously during the testing period.

---

* Corresponding author. Address: Transmission and Distribution Laboratory, Korea Electric Power Research Institute, Munjiro-65, Yusung-Gu, Daejeon, 305-380, Republic of Korea. Tel.: +82 42 865 5912; fax: +82 42 865 5809.
E-mail address: jhlim06@kepri.re.kr (J.H. Lim).

0921-4534/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2010.05.170

Please cite this article in press as: J.H. Lim et al., Physica C (2010), doi:10.1016/j.physc.2010.05.170

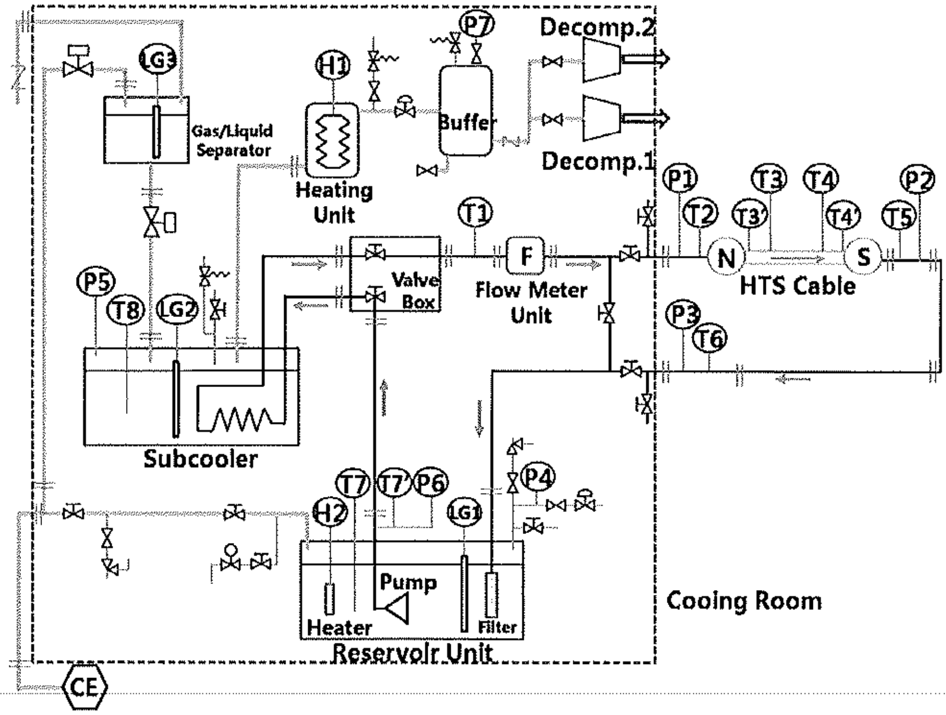

Fig. 1. Diagram of the decompression cooling system.

Table 1
Heat loss dependence on thermal cycle test.

Heat loss @ 66.4 K and $F = 40$ L/min (no load)	Total system (kW)	Source termination (kW)	Load termination (kW)	Cable (kW)
2nd cooling	1.19	0.21	0.34	0.23
3rd cooling	1.32	0.24	0.34	0.22
4th cooling	1.33	0.22	0.36	0.25
5th cooling	1.19	0.20	0.33	0.26
6th cooling	1.19	0.20	0.32	0.26
7th cooling	1.18	0.20	0.34	0.26
8th cooling	1.20	0.19	0.35	0.26
9th cooling	1.30	0.21	0.38	0.28

Table 2
Verification test of cooling capacity.

Time	Condition	LN_2 supply frequency of subcooler	Total loss (kW)
4.30 h	0 A	8 (1.784/h)	1.21
9.30 h	800 A	19 (2.014/h)	1.66
11 h	800 A + 0.5 kW	27 (2.458/h)	2.12
14 h	800 A + 1.0 kW	46 (3.266/h)	2.73
17 h	800 A + 1.5 kW (single pumping)	65 (3.801/h)	–
23 h	800 A + 1.5 kW (dual pumping)	92 (3.673/h)	3.23

2.2. Verification test of cooling capacity

Cooling system response and maximum cooling capacity were verified through applying AC current and a heater. Heat loss from applying AC current and using an electrical heater inside the reservoir unit was measured under various conditions. With the operation condition was 66.4 K and 40 L/min, the heater input changed from 0 kW to 1.5 kW when 800 A_{rms} was applied. When 800 A_{rms} and 1.5 kW heater input were simultaneously applied, cable inlet (T3), outlet (T4), and operation temperature (T1) increased continuously. The fluctuation of the operation temperature was 0.6 K with 1.5 kW heater input. In case of the speed of LN_2 supply from gas/liquid separator to subcooler, 1.784 times per hour when the heat input was not applied, however, the frequency increased to 3.226 times per hour with heater input of 1.0 kW as shown in Table 2. In conclusion, the maximum cooling capacity of the cable system was 2.73 kW with single decompression pump and it could be 3.23 kW with dual decompression pumps; two decompression pumps (described in Fig. 1).

2.3. Unbalanced load test

When currents were applied to the HTS cable, it was designed that the same amount of currents were theoretically induced in the shield layers. In previous work, we already performed the load test under the three phase balanced operation condition [4]. However, in the practical power grid, maximum 30% unbalanced load rate among the phases can occur. In particular, in case of HTS cable, non-uniform current distribution among the conductors creates different induced currents in the shield layers. Consequently, unbalanced condition of the shield layer could affect mutual magnetic interference variation between conductor and shield layer and cause to generate AC loss. In this reason, we carried out the unbalanced load test to simulate the situation of practical power grid. Fig. 2 shows the configuration of the test circuits. For the tests, besides the HTS cable of KEPCO, an HTS cable produced by LS cable Ltd. was also applied. Both HTS cables were connected as presented in the figure and the currents were applied to the cables.

$$R = \frac{I_{max}\ (A, B, C) - I_{min}\ (A, B, C)}{\frac{I_A + I_B + I_C}{3}} \times 100\% \qquad (1)$$

Please cite this article in press as: J.H. Lim et al., Physica C (2010), doi:10.1016/j.physc.2010.05.170

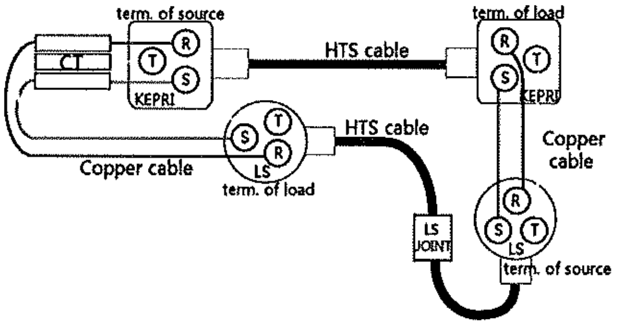

Fig. 2. Electrical circuit of KEPCO and LS Cable's HTS cable.

Unbalanced load rate (R) was defined by Eq. (1). As presented in Fig. 3a and b, the currents were applied to conductors and shield layers with 800 A–800 A–1067 A and 850 A–1000 A–1150 A (30% unbalanced rate) respectively. Since the current distribution was changed, the induced current of each shield layer became different. In this case, since the magnetic field was changed in accordance with the layer structure, pitch of wire winding and gap among the superconducting wires, hysteresis loss of the HTS cable increased during the operation.

3. Preparation of hybrid cooling system

Through the tests, the properties of the HTS cable system and operational characteristics were investigated. However, the decrease of loss generated in HTS cable system was not took into consideration because it was dependent on the specification of the HTS cable. In particular, since the LN_2 consumption during the tests was considerably larger than expected, we decided to make an effort to increase the cooling efficiency through the preparation of new type of cooling system. For the purpose, we adopted hybrid cooling system, which is combined a stirling cryocooler produced by Stirling Cryogenics and Refrigeration BV, Netherlands. In previous study, when 1250 A_{rms} was applied to the HTS cable, the heat loss of 2.4 kW was generated under the condition of 66.4 K operation. Based on the results, a stirling cryocooler, in which the cooling capacity was 4 kW at 77 K (2.8 kW @ 65 K) was chosen for an additional machine to increase the cooling efficiency. In this system, input power of the cryocooler was 40 kW at 77 K and the chiller consumed the power of 48 kW for cooling water. In order to verify the cooling system with each cooling mode such as the decompression type, stirling cryocooler, and hybrid cooling type, we constructed a hybrid cooling system as described in Fig. 4a. The hybrid cooling system is consisted of the open-loop cryogenic system and the new type of stirling cryocooler. The cooling capacity of cooling system using decompression pump and the stirling cryocooler are

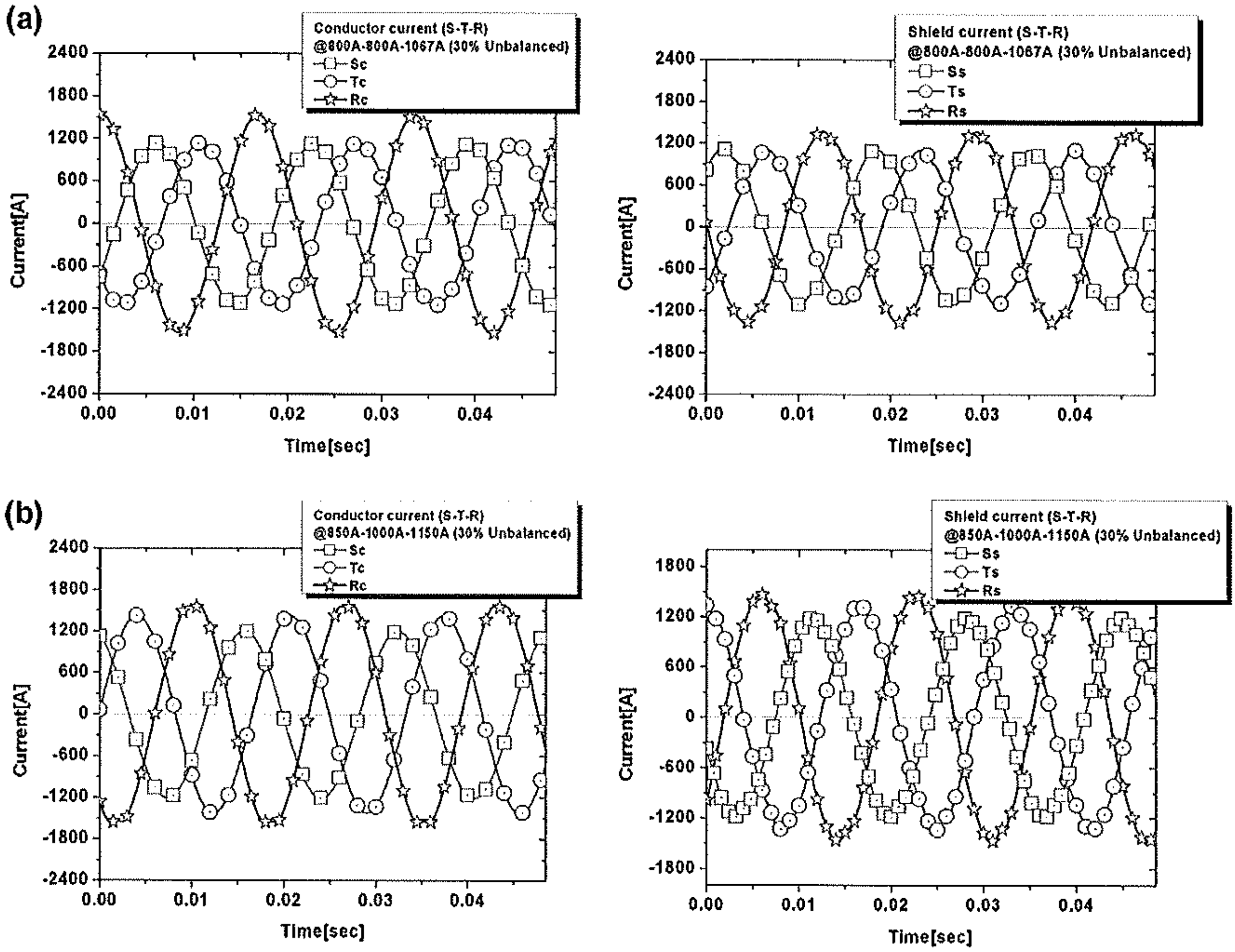

Fig. 3. (a) 800 A–800 A–1067 A (30%) conductor and shield current waves and (b) 850 A–1000 A–1150 A (30%) conductor and shield current waves.

Please cite this article in press as: J.H. Lim et al., Physica C (2010), doi:10.1016/j.physc.2010.05.170

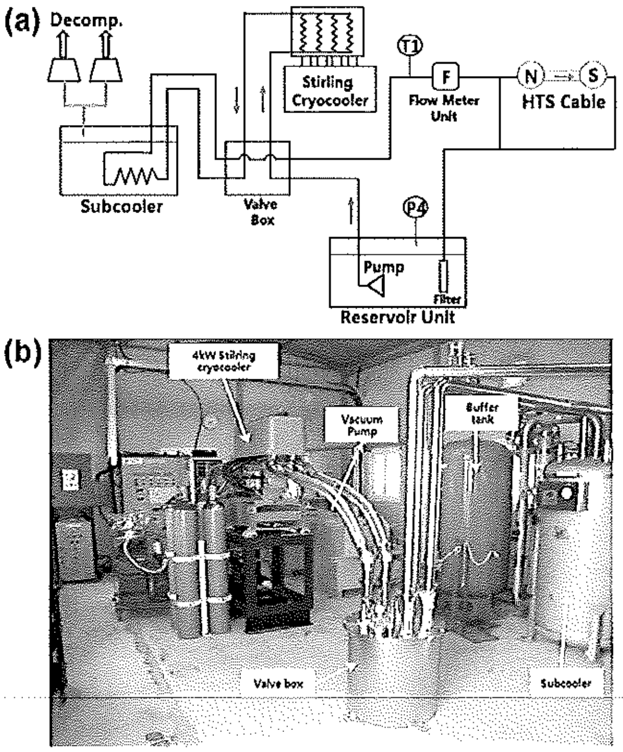

Fig. 4. (a) Schematic of the hybrid cooling system and (b) picture of the hybrid cooling system.

3 kW and 2.8 kW at 66.4 K, respectively. Therefore, the hybrid type cooling system can achieve up to the cooling capacity of 5.8 kW at 66.4 K. As shown in Fig. 4b each cooling mode was regulated by controlling valves in the cooling system. At present, the installation of the hybrid cooling system is finished and the performance test is in progress. In 2009, KEPCO launched a project for the real field operation of HTS cable of 500 m in length. The test results of the test will be used for the project.

4. Summary

Since 2005, a 22.9 kV, 1250 A, 100 m class HTS cable system has been tested in Gochang Power Testing Center, Korea. In this paper, the dependence of heat loss on thermal cycle test, verification of cooling capacity, and the test results of unbalanced load operation were presented. The decompression cooling system installed at the beginning showed reliable and stable operation through various electrical and thermal tests. However, the loss of LN_2 was too large to satisfy the operational efficiency expected during the test. In order to improve the problems, a hybrid type cooling system was designed and assembled for the further study. A stirling cryocooler with the cooling capacity of 4 kW at 77 K was employed additionally and composed with the decompression cooling system. At present, the hybrid cooling system is tested for the operation of the HTS cable system and the results will be used for another KEPCOs project for the real application of HTS cable system scheduled at Ichon power substation in Korea.

Acknowledgments

This work was supported in part by the Korea Institute of Energy Technology Evaluation and Planning (KETEP), an agency of the Korean government Ministry of Knowledge Economy (MKE), Republic of Korea.

References

[1] S.H. Sohn, J.H. Lim, S.W. Yim, O.B. Hyun, H.R. Kim, K. Yatsuka, S. Isojima, T. Masuda, M. Watanabe, H.S. Ryoo, H.S. Yang, D.L. Kim, S.D. Hwang, IEEE Trans. Appl. Supercond. 17 (2007) 2043.
[2] J.H. Lim, S.H. Shon, H.S. Yang, D.L. Kim, H.S. Ryoo, S.D. Hwang, Adv. Cryogen. Eng. 53 (2008) 1209.
[3] S.H. Sohn, J.H. Lim, H.S. Yang, D.L. Kim, H.S. Ryoo, C.D. Kim, D.H. Kim, S.K. Lee, S.D. Hwang, Adv. Cryogen. Eng. 53 (2008) 1217.
[4] J.H. Lim, S.H. Shon, H.S. Ryoo, H.O. Choi, H.S. Yang, D.L. Kim, Y.H. Ma, K. Ryu, S.D. Hwang, IEEE Trans. Appl. Supercond. 19 (2009) 1710.
[5] H.S. Yang, D.L. Kim, S.H. Sohn, J.H. Lim, H.O. Choi, Y.S. Choi, B.S. Lee, W.M. Jung, H.S. Ryoo, S.D. Hwang, IEEE Trans. Appl. Supercond. 19 (2009) 1782.

Please cite this article in press as: J.H. Lim et al., Physica C (2010), doi:10.1016/j.physc.2010.05.170