Investigation on Effective Operational Temperature of HTS Cable System considering Critical Current and AC loss

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Abstract

The operational cost for maintaining the superconductivity of high-temperature superconducting (HTS) cables needs to be reduced for feasible operation. It depends on factors such as AC loss and heat transfer from the outside. Effective operation requires design optimization and suitable operational conditions. Generally, it is known that critical currents increase and AC losses decrease as the operational temperature of liquid nitrogen (LN₂) is lowered. However, the cryo-cooler consumes more power to lower the temperature. To determine the effective operational temperature of the HTS cable while considering the critical current and AC loss, critical currents of the HTS cable conductor were measured under various temperature conditions using sub-cooled LN₂ by Stirling cryo-cooler. Next, AC losses were measured under the same conditions and their variations were analyzed. We used the results to select suitable operating conditions while considering the cryo-cooler’s power consumption. We then recommended the effective operating temperature for the HTS cable system installed in an actual power grid in KEPCO’s 154/22.9 kV transformer substation.

Keywords : HTS cable, effective operational temperature, critical current, AC loss

I. INTRODUCTION

High temperature superconducting (HTS) cable does not make Joule heating during current flows, which means that no ohmic loss occurs in normal operation state. Using these characteristics, design of underground cable with large power capacity and compact size could be possible; it can be applied to retrofit conventional cable with new one with low voltage and large power capacity. However, since the HTS cable is operated under cryogenic state, the operational cost is too high to utilize it as a practical use. To reduce the operational cost, several plans can be considered such as reduction of AC loss through thermally well-made design and fabrication, use to cryo-cooler of high efficiency, and optimization of operational condition to save energy consumption. On the other hand, critical current, which is closely related to a rated current, of HTS cable can be changed with the operational temperature. Since the cooling capacity of a cryo-cooler is larger at a higher operational temperature, in AC application that the current varies at all times with power demand, power consumption can be expected to save the control of operational temperature of HTS cable. However, AC loss, in general, is inversely proportion to the critical current of HTS cable [1]. In this study, considering above relationship among the factors, we measured critical currents and AC loss with various temperature conditions and analysis the effective operational temperature, using real-scale HTS cable and large scale cryo-cooler.

II. TEST ON OPERATION OF HTS CABLE SYSTEM

For the investigation on the condition of HTS cable operation, we tested an HTS cable system consist of HTS cable and cooling system.

A. HTS cable

The HTS cable tested in this study was the one of a 22.9 kV/50 MVA, 91 m in length, which was introduced to Gochang power testing center at KEPCO site in 2005. The specification of the HTS cable is described in Table 1. A lot of tests were carried out on this HTS cable including more than 2 years of long-term operation. For this study, the HTS cable was cooled and re-energized. For the confirmation on degradation due to any defect, the property was tested through the measurement of critical current. As the result, critical currents, which are presented in Fig. 2(a), were not changed compared to origin. In addition, AC loss was also measured. It was also the same to the result previously shown. Fig. 2(b) shows a case of AC loss measured when currents were applied to the HTS cable.

B. Cooling system

In this study, a Stirling type cryo-cooler was taken into account for cooling the HTS cable. As shown in configuration of Fig. 2(a), totally four sets of Stirling cooler were assembled to become a large scale cryo-cooler of 4 kW cooling capacity at 77...
K. In Fig. 2(b), actual measured cooling capacity of the Stirling cooler used in this study, which is varied with operation temperature, is demonstrated. From Fig. 2, we can see that the cooling capacity decrease as the operation temperature is decreased, and it becomes around 2.8 kW at 66 K. In this cooling system, some of extra machines must be additionally required for the operation of Stirling cooler unit. The Stirling cooler is driven by an induction motor and an inverter. In addition, a chiller is also demanded for the mechanism of heat exchange in the Stirling cooler. In this reason, we had to consider the total power consumption including the machines for the evaluation of the operational cost. Fig. 3 shows the required electric power consumed by the Stirling cooler in a certain condition varying with heat load. The cooling capacity and power consumption of Stirling cooler is controlled with cooling load in a range from 60% to 100% output.

C. Operational characteristics

According to Fig. 3, one can expect that the power consumption can be reduced through the control of the operation temperature in Stirling cooler. In case of HTS cable application, the critical current is changed, being proportion to the cooling temperature. Therefore, if the load is small, the operating temperature could be raised so that it makes lower power consumption. Fig. 4(a) and (b) show the variation of critical current and AC loss with temperature. As expected, critical current is varied, being inversely proportion to cooling temperature. In Fig. 4(b), the variation of AC loss with applied current and temperature is presented. Differently from critical current, AC loss becomes higher as cooling temperature increases. Based on the result in Fig. 4(a) and (b), cooling capacity required for effective operation can be acquired. In Fig. 3, if we assumed that 50% of critical current is designed as the rated current (I_{rms}), when 1,000 A_{rms} flows through the HTS cable, the cooling temperature should be maintained below 67 K, because 3000 A of critical current can be acquired at this temperature. In addition, Fig. 3 shows that AC loss of 300 W will be generated in this condition. However, in case that only 600 A_{rms} flows though the HTS cable, the HTS cable can be operated at 76 K. The critical current at 76 K is over 1700 A and AC loss is 110 W when 600 A_{rms} flows. According to Fig. 4(c), when the current is varying, for instance, from 1,000 A_{rms} to 600 A_{rms}, we can 30% of power consumption can be saved by controlling the operational temperature from 67 K to 76 K.

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**Table 1. Physical properties of HTS cable**

| Property                        | Value                  |
|---------------------------------|------------------------|
| Rated Voltage                   | 22.9 kV                |
| Rated Current                   | 1,250 A                |
| Capacity                        | 50 MVA                 |
| Length                          | 100 m                  |
| Cable Type                      | 3 cores in one cryostat|
| Dielectric Type                 | Cold dielectric        |
| Cable Size                      | Applicable for 175 mm duct |
| Response to Fault Current       | 25 kA / 5 cycles       |
| Former                          | Cu-stranded wire, 16 mm|
| Conductor                       | Bi-2223 tape, 2 layers |
| (Number of tapes : 23)          |                        |
| Electrical Insulation           | PPLP, 4.5 mm           |
| Superconducting Shielding       | Bi-2223 tape, 1 layers |
| (Number of tapes : 19)          |                        |
| Protection Layer                | Cu tape + Insulation Paper |
| Cable Outer Diameter            | 130 mm                 |

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**Fig. 2. Characteristics of the Stirling cooler used in this study. (a) configuration, (b) cooling capacity.**

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**Fig. 3. Power consumption for Stirling cooler system. (a) when fully operated, (b) variation with cooling load.**

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**Fig. 4. (a) Variation of critical current with temperature. (b) Variation of AC loss with applied current and temperature. (c) Power consumption for effective operation.**
Based on the data in Fig. 3 to Fig. 4, we analyze the case of actual power grid operation. In a KEPCO’s 154/22.9 kV transformer substation, a 22.9 kV/50 MVA class HTS cable had been operated for 19 months [2][3]. Fig. 5 shows the variation of load that the HTS cable experienced. As expected, the power load was varied seasonally. The maximum peak load was 42 MW of which the current was around 1,000 Arms (The zones denoted as a and c in Fig. 5). In addition, around 600 A rms flowed during seasons of spring and fall, when the power demand was smaller (The zone of b in Fig. 5). Fig. 6(a) shows a daily load variation occurred in the HTS cable. Since the power demand is also changed continuously, the required cooling power will be varied as stated in previous section. Although the HTS cable was operated under the condition of 69 K without change in actual operation, accordingly to Fig. 4, the operational temperature would be changeable so that the power consumption could be saved.

**III. ACTUAL POWER GRID OPERATION**

Based on the data in Fig. 3 to Fig. 4, we analyze the case of actual power grid operation. In a KEPCO’s 154/22.9 kV transformer substation, a 22.9 kV/50 MVA class HTS cable had been operated for 19 months [2][3]. Fig. 5 shows the variation of load that the HTS cable experienced. As expected, the power load was varied seasonally. The maximum peak load was 42 MW of which the current was around 1,000 Arms (The zones denoted as a and c in Fig. 5). In addition, around 600 A rms flowed during seasons of spring and fall, when the power demand was smaller (The zone of b in Fig. 5). Fig. 6(a) shows a daily load variation occurred in the HTS cable. Since the power demand is also changed continuously, the required cooling power will be varied as stated in previous section. Although the HTS cable was operated under the condition of 69 K without change in actual operation, accordingly to Fig. 4, the operational temperature would be changeable so that the power consumption could be saved.

**IV. CONCLUSION**

In order to investigated the effective operational temperature of an HTS cable, the relationship between operational temperature and critical current and AC loss. Using real-scale of HTS cable system, critical current and AC loss were measured with various temperature conditions. The critical current...
increased almost linearly as the cooling temperature was decreased. In addition, as the cooling temperature became higher, AC loss increased. On the other hand, a Stirling cryo-cooler was tested and evaluated for the investigation of effective operational temperature. The power capacity of the Stirling cooler was varied with the operating temperature, which was 4 kW at 77 K and 2.8 kW at 66 K. Since the power consumption is inversely proportion to the operating temperature, it was concluded that the operational cost for an HTS cable can be saved by controlling the operational temperature. Finally, we proposed data for an HTS cable operation so as to evaluate the effective operational temperature.

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