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Long-term test of the 22.9kV HTS power cable system in LS Cable Ltd.

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Abstract. Since 2001, LS cable Ltd. has been developing the design, manufacturing and evaluation technologies for high temperature superconducting (HTS) power cable system as a member of DAPAS (Dream for Advanced Power system by Applied Superconductivity technology) program in Korea. The 30 m HTS cable system that is rated at 22.9 kV and 1.2 kA giving a rated capacity of 50 MVA had been developed and tested. The cable was designed as a cold dielectric type employing Bi-2223 HTS tapes and polypropylene (PP) laminated paper as the conductor and electrical insulation, respectively. The cable is cooled with sub-cooled liquid nitrogen at temperature from 75 to 77 K. The manufacturing and the installation of the cable system were completed in 2004. Long-term performance test of the cable system has been conducted for six months to verify its electric and mechanical properties in 2005.

1. Introduction
In the next years, the power demand is expected to increase by 4 to 5 percents, every year, and the peak demand in 2010 is expected up to 60GW in Korea. Especially, the rising concern about high electric load density in the metropolitan area makes it important to find new technologies to improve the reliability of power transmission systems and the reduction of transmission losses. HTS cable is regarded as one of the most promising technologies to solve these issues due to its high transmission capacity and very low impedance. To lead the future power grid technology in Korea, LS Cable Ltd. has been developing HTS cable system from 22.9 kV to 154 kV since 2001 as a member of DAPAS program.

HTS cable system that is rated at 22.9 kV, 1.2 kA and 60 Hz giving a rated capacity of 50 MVA had been successfully manufactured and installed in 2004, based on the experience of 22.9 kV single core HTS cable system in 2003\cite{1}. The cable consists of the core employing Bi-2223 HTS conductor and PP laminated paper insulation, and the cryostat employing aluminum pipes. This paper describes the long-term performance tests of 22.9kV HTS cable system conducted for six months in 2005.

2. 22.9kV HTS cable system
The HTS cable is rated at 22.9 kV, 1.2 kA and 60Hz giving a rated capacity of 50 MVA. The cable is cooled with pressurized liquid nitrogen at temperatures from 75 to 77K using cryogenic system. The specifications of the test cable system are described in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Parameter & Specification & Notes \\
\hline
Voltage & 22.9 kV & \\
Current & 1.2 kA & \\
Frequency & 60 Hz & \\
Capacity & 50 MVA & \\
\hline
\end{tabular}
\caption{Specifications of the 22.9kV HTS cable system.}
\end{table}
Table 1. Specifications of the HTS cable system

| Electrical characteristics          |
|------------------------------------|
| Rated voltage & current            | 22.9 kV<sub>rms</sub>, 1.2 kA<sub>ms</sub> |
| Rated capacity                     | 50 MVA                                           |
| HTS cable & termination            |
| Cable type/length                  | 3 core, 30m                                      |
| HTS phase conductor & shield       | Bi-2223 tapes delivered by AMSC & InnoST         |
| Electrical insulation              | Cold dielectric(polypropylene laminated paper)   |
| Termination                        | Six outdoor termination & two splitter           |
| Cryogenic system                   | Hybrid refrigeration system (Cryo-cooler & decompression cooling system) |

2.1. HTS cable and termination
The cold dielectric and three cores cable was selected to meet the application requirement in Korea. To provide the 1.2 kA<sub>ms</sub> capacity, the phase conductor and shield assembly used two layers of Bi-2223 tapes, respectively. The tapes, which were delivered by American Superconductor (AMSC) and have an average critical current (I<sub>c</sub>) of 115 A, were used for phase conductor. The tapes, which were delivered by InnoST and have an average I<sub>c</sub> of 80 A, were used for shield. The conductors were designed to share the transport current evenly in each tapes and layers by solving the equivalent circuit of the cable. The electrical insulation was made by polypropylene laminated paper with the thickness of 4.6 mm [2]. The cryostat consists of seamless type aluminum pipes fabricated by extrusion and multi layers of thermal insulation. Figure 1 shows the configuration of the HTS cable.

Six terminations and two splitters have been developed for the test of 30 m HTS cable. The termination is the interface from the HTS conductor operating in a pressurized liquid nitrogen environment to conventional conductor operating at room temperature at atmospheric pressure. The current lead in the termination is a large source of the heat invasion due to the high thermal conductivity of copper. Therefore the computer simulation was conducted to find optimal geometry of the current lead in various loading conditions.

2.2. Cryogenic system
The HTS cable and the terminations are cooled by pressurized and sub-cooled liquid nitrogen circulating through the inside of the HTS cable. For the cool down and the operation of 30 m HTS cable and terminations, the hybrid type refrigeration system had been developed. One is pulse tube cryo-cooler system for the 30 m cable, and the other is the decompression cooling system for the six terminations. These two refrigeration systems not only cool down each liquid nitrogen loop individually but also exchange the heat with each other.
2.3. Installation
The 30 m HTS cable system shown in figure 2 was installed at a test site in Gumi factory of LS Cable Ltd. and the cable was bent in U-shape with bending radius of 5 m. The test system for electrical test consist of SF6 immersed termination, three outdoor terminations, the high voltage tester and three set of outdoor terminations.

3. Long-term test
As shown in figure 3, long-term performance tests had been carried out for six months in 2005. DC current test, withstand voltage test and ac loss measurement were performed at pre-test period, and were repeated at long-term test period.

|                  | Jan. | Feb. | Mar. | Apr. | May   | Jun. | Jul. |
|------------------|------|------|------|------|-------|------|------|
| Pre-test         |      |      |      |      |       |      |      |
| Long-term test   |      |      |      |      |       |      |      |
| 1st Cool down    |      |      |      |      |       |      |      |
| 2nd Cool down    |      |      |      |      |       |      |      |
| 3rd Cool down    |      |      |      |      |       |      |      |

Figure 3. Test schedule of 30 m HTS cable system.

3.1. DC current test
The DC voltage/current test was performed to measure DC voltage versus current relationship. The V-I curves for 30 m cable system including terminations and the sample from the installed cable are shown in figure 4. In the 30 m cable system, voltage taps were temporarily installed external to the main bushings. As can be seen in figure 4, the sample maintained a DC Ic of approximately 4.3 kA, which corresponds to the designed value. In case of 30 m test loop, the linear behavior over most of the current range is due to the extensive copper current lead and joint part beyond each end of the HTS cable. Considering HTS tapes performance, the DC Ic of the 30 m HTS cable is expected to exceed 3 kA.

3.2. Cool down and load cycle test
Cool-down and warm-up cycles were repeated more than 3 times under variable loading conditions to determine cable performance. Figure 5 shows the history of the temperature and vacuum rate of the cable and cable cryostat, respectively, during six months. The vacuum properties of our aluminum cryostat had been heavily affected by the cable temperature [3]. During the cool downed state, the cryostat maintained high vacuum state with the vacuum rate of less than 1×10⁻⁴ torr without additional pumping.

The rated line-to-ground voltage of 13.2 kV and the current of 630 A to 1.2 kA, as shown in figure 6, were loaded to the cable for 2,200 hours during the load cycle test period. The daily load pattern...
was determined by load pattern in Korea. Heat loss and ac transport current loss of the cable was measured by the calorimetric method at various loading condition. The averaged heat loss at the 77 K was about 3.52 W/m, and AC transport current loss was 1 W/m/phase at 1.2 kA.

3.3. Withstand voltage test

After 2,200 hours of load test period, the voltage of ac 80 kV and impulse ±170 kV was applied for an hour and 10 times, respectively, to the cable for measuring the withstand voltage characteristics. During the AC voltage test, partial discharge was not observed in the sensitivity of approximately 20 PC. The overall test results are described in table 2.

Table 2. Test results of 30m long HTS cable system in LS Cable Ltd.

| Item               | Results                                      |
|--------------------|----------------------------------------------|
| Heat loss          | 3.52 W/m (including U-shape bending)         |
|                    | 1.5 W/m (straight part)                      |
| AC loss @1.2kA, 77K| 1 W/m/phase                                  |
| Load test period   | More than 2,200 hours (92 days)              |
| High voltage withstand test | AC 80 kV/1hr, Imp. ±170 kV/10 shot  |
| Thermal cycle      | More than 3 times (No Ic degradation)        |

4. Conclusion

Long-term test of the HTS cable system that is rated at 22.9 kV and 1.2 kA giving a rated capacity of 50 MVA has been carried out for six months in LS Cable Ltd. The line-to-ground voltage of 13.2 kV and the current of 630 A to 1.2 kA have been loaded to the cable and terminations for about 2,200 hours, considering daily load pattern in Korea. Cool-down and warm-up cycles were repeated more than 3 times under variable loading conditions to determine cable performance. Most of the test results were well agree with the design.

Based on the experiences of developing 22.9 kV, 30 m HTS cable systems, new design of 22.9 kV HTS cable for the real network, and development of 154 kV HTS cable system are underway.

References

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