**Design of 23kV 50MVA class HTS Cable in South Korea**

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**Abstract.** The world first commercial project for the superconducting applications is already starting in South Korea. The first step of the project named SSS (Superconducting Smart platform Station in South Korea) is to operate AC 23kV 50MVA class HTS cable system in the power grid of Korea Electric Power Corporation (KEPCO) in order to increase the power capacity and realize the stable operation. The above HTS cable system will connect two substations between ShinGal and HeungDuk. Total length of the HTS cable is approximately over 1km including 2 sets of the normal joint box and 2 sets of the termination which are the out-door type accessories. Before performing the type test, various preliminary tests with the short cores were performed to confirm design of the HTS cable. To meet the design goals, the HTS layers of the core consist of the two conducting and one shield layer. The characteristics of the HTS wire is the non-magnetic 2nd generation wire. It can reduce the magnetization loss caused by itself and adjacent the HTS wires. The measured AC loss is around 0.3 W/m at 1,260 Arms and increasing trend of AC loss by operating current is the well fitted of simulation results. In case of short-circuit test, experimental temperature is approximately 77K and increased maximum temperature is under 92.8 K which is enough below the boiling temperature of LN2 at gage pressure 6.7bar.(g). A 70-meter-long the HTS cable including unit the test samples and an 85-meter-long LN2 return pipe will manufacture and installed for the type test at KEPCO Power Training Center in Gochang, South Korea. The type test procedure is following the Cigre TB538 and KEPCO standard those are including the 20 cycles load test, voltage tests such as AC withstand and impulse, repeated cooling process three times as prequalification quality test and visual inspection after disassembling. In the third quarter of 2018, LS Cable&System will supply and install AC 23kV HTS cable system in South Korea.

**1. Introduction**

SUPERCONDUCTING APPLICATIONS using the high temperature superconductor (HTS) such as cable, the rotating machines and the superconducting fault current limiter are applicable in the real power grid with the stable operation [1-2]. The superconducting applications such as the HTS cable, the motor and the SFCL for the power grid are state-of-the-art technology. Especially, the HTS cables can transfer the large capacity power source with low losses, and are expected to be not only environmental applications but also application with electromagnetic interference free performance which means no influences of adjacent other cables. It has a compact size compared with the conventional power apparatus. However, these apparatus such as HTS cable have to consider easy connection with the existing applications in the power grid. Thus, the various R&D projects were performed and the demonstration projects were being promoted in the world.

Since 2001, Korea Electric Power Corporation (KEPCO), LS Cable&System (LS C&S) and various institutes have been cooperating national R&D program that was Development of Advanced Power system by Applied Superconductivity technologies (DAPAS) funded by the Ministry of Education, Science and Technology in South Korea. During the 10 years of DAPAS program, the basic design...
concept of distribution and transmission level HTS cable system was established and manufactured the HTS cable for type test to verify design factor for applying power grid. The HTS cable even distribution level can have bulk power capacity like conventional cable in transmission level which means it can replace existing conventional transmission cable and save cost of the civil work for installation of extra cable in the power grid. Thus, KEPCO and LS C&S installed 23kV 50MVA class HTS cable in the Incheon substation. This HTS cable system was approximately 500 meters including 2 sets of the outdoor termination, 1 set of the normal joint-box and 1 set of decompression type as cryo-cooler. Type of this HTS cable was 3 Phase-in-One cryostat type and the unmanned operation at the Incheon substation was conducted 18 months among 20 months. The next step was increasing the transmission capacity as 23kV 120MVA. Installation route of next project was approximate 100 meters. These demonstration schedules were called the Green Superconducting Electric Power Network at Icheon Substation (GENI). Furthermore, the demonstration of AC 154kV 600MVA HTS cable system and DC 80kV 500MW HTS cable system in Jeju Island was performed to investigate the stability and the operation condition in the real power grid. To verify performance and reliability of the HTS cables, our research group performed design of the HTS cable system based on several FEM simulations such as the calculation of current distribution according to the various pitch values of each HTS layer, the calculation of AC loss, and the thermal contraction force during the cool-down and the warm-up. Based on above design process, the HTS cables with short length were manufactured and measured preliminary test according to TB538 and KEPCO’s standard. From the above the preliminary tests and the demonstration in Jeju site and Ichecho substation, LS C&S developed and demonstrated the world first HVDC HTS cable, which was bipolar type of DC ±80kV 500MW class and total length was 500 meters, and the highest voltage and the longest length cable as AC 154kV 600MVA class HTS cable in Jeju site. In case of AC 154kV HTS cable in Jeju site, the one phase cable length was over the 1km and experienced various installation conditions that are through the pipe duct and ground over and over again of the 1km. This system consists of the three phases of 154kV, the six outdoor type terminations, the six normal joints and the one set of the cooling system (10kW@69K). It was energized in 2016. Especially, the terminations of those DC and AC HTS cable were applied the fixed-type termination. It can withstand thermal contraction force during the cool-down and the warm-up. It means that the thermal contraction force can be absorbed by the installation method using the snake shape in a straight section of the cable installation route in the power grid.

Based on the experience and the results from DAPAS program, GENI program and Jeju demonstrations, the world first commercial HTS cable project has launched by KEPCO in 2016 that is named SSS (Superconducting Smart platform Station in South Korea) project. The main goal of SSS project is established commercialization stage and making test-bed of the smart platform in South Korea. 3-Phase in One Cryostat type of the HTS cable will manufacture 1,035-meter-long to transfer power between ShinGal and HeungDuk substations and return pipe will manufacture 1,040-meter-long for circulation of LN2. Table 1 and table 2 represent system requirements of AC 23kV 50MVA class HTS cable system in the power grid. The first stage of ShinGal project is setting up cryogenic system which is using Reverse Turbo Brayton type cryo-cooler made by Taiyo Nippon Sanso (TNSC) in Japan. Next step is performing the type test of AC 23kV 50MVA class HTS cable with 2 set of outdoor type termination and 1 set of normal joint box. Procedure of type test is complied with TB538, which was published by Cigre Working Group, and KEPCO’s standard. The voltage level and power capacity of this project is 23kV 50MVA class and various types of HTS wires will apply. The cryo-cooler was already installed in HeungDuk substation. Now LS C&S is preparing type test at KEPCO’s Power Testing (PT) center. The installation of the HTS cable will complete in the second quarter of 2018.

Figure 1 shows a diagram of the HTS cable system of the ShinGal project. Dot line explains of flowing direction of LN2 in the HTS cable system including return pipe. Accessories for the return pipe also need. Configuration of the return pipe is similar to the double metal sheath of the HTS cable. The 1st metal sheath is making area for flowing LN2 and the 2nd metal sheath is making another wall to make vacuum status. Thus, the double metal sheath is blocking the heat invasion between inside and outside of the HTS cable. The multi insulation layer (MLI) also applied to reduce light penetration. Finally, thermal spacer also added to avoid and minimize contact area of the 2nd metal.
Table 1. The Power Grid Conditions by KEPCO.

| Item                     | Unit | Requirement |
|--------------------------|------|-------------|
| Nominal Voltage          | kV   | AC 23       |
| Power Capacity           | MVA  | 50          |
| Rated Current            | A    | 1,260       |
| HTS Cable Length         | m    | 1,035       |
| Return Pipe Length       | m    | 1,040       |
| Ground                   | -    | Sheath      |
| BIL                      | kV   | 150         |
| Short Circuit Current    | kA/sec | 25/0.5    |

Table 2. Installation Status and Operation Conditions.

| Item                               | Unit | Requirement                  |
|------------------------------------|------|------------------------------|
| Installation Condition             | -    | Duct / Tunnel / Ground       |
| Cable Construction                 | -    | 3-Phase in One Cryostat     |
| No. of Termination / Joint box     | set  | 2 / 2                        |
| Pressure Range in Normal Term     | bar(g) | 7.60 ~ 6.70                 |
| Temperature Range in Normal Term   | K    | 69.0 ~ 74.8                  |
| Instantaneous Max. Temperature     | K    | 92.8                         |
| during the Fault Accident          |      |                              |

Figure 1. Diagram of the ShinGal Project.

2. Preliminary Test

Table 1 shows requirements of the power grid. Firstly, LS C&S was doing the engineering design of the whole system such as a pressure drop and the difference temperature between the inlet and the outlet of the HTS cable based on the installation status. Table 2 shows engineering design of AC 23kV 50MVA HTS cable system between ShinGal and HeungDuk substations. To make compact size and
competitive price, the core configuration such as a former size, number of the HTS wires, the pitch of the HTS wire layers and the PPLP insulation thickness was designed based on the preliminary test results and productivity conditions.

The former made of thin and of round type copper stranded wires avoids skin effect during the operation. Applicable magnitude of current in each HTS wire layer could be calculated by outlet temperature of the HTS cable because the critical current of the HTS wire should be changed by temperature of LN₂. Furthermore, current distribution between the HTS layers with non-magnetic subtract such as hastelloy and stainless steel must be investigated. For increasing mechanical strength of the HTS wire, lamination material such as copper and brass could be adapted to withstand any stress during the manufacturing process and installation of the HTS cable. The double aluminium cryostats with corrugated type were also adapted to make LN₂ channel and to make vacuum wall. After manufacturing short length of the HTS cable, it was cut to investigate and its results compared with the previous design concept.

The inner diameter of duct pipe in the power grid is 200mm. Thus, the maximum diameter of the HTS cable diameter should be limited under approximate 153mm. Then the HTS cable could be installed without extra construction of tunnel and duct.

2.1. Manufactured Sample Cable
To perform the preliminary tests, the sample cables were manufactured based on the previous design value. Two kinds of HTS wires were used in these sample cables for investigating its feasibility and performance during the manufacturing and test. Total number of conducting layer and shield layer is 2 layers and 1 layer, respectively. The calculated AC loss of shield layer was generally much less compared with conducting layer. It means that the HTS wire with the high critical current should be arranged in the conducting layer for the reducing AC loss if other design factors were perfectly same. The short core of Core #1 and Core #3 has similar critical current of the conducting layer except the shield layer. The different amount of critical current at shield layer between the Core #1 and the Core #3 is around 1,000 A. However, core configuration such as pitch, wire number, insulation thickness and layer number is perfectly same among three cores. Table 3 shows the critical current of each core and measured temperature is 77.3 K [4]. In case of Core # 3, the HTS wires of conducting and shield layer was made by SuNAM and AMSC.

| Item   | Conducting Layer | Shield Layer | Wire Manufacture |
|--------|------------------|--------------|------------------|
| Core #1 | 5,623.0 A        | 3,712.0 A    | SuNAM            |
| Core #2 | 3,439.0 A        | 2,731.0 A    | AMSC             |
| Core #3 | 5,608.0 A        | 2,718.0 A    | Conducting Layer : SuNAM  
              Shield Layer        : AMSC          |

2.2. The Bend Test
The diameter for the bending test follows Cigre TB538 which is international recommendation for the AC HTS cable [5]. However, bending diameter at Cigre TB538 is too larger than applicable steel drum diameter. Table 4 shows diameter of the bend test where small d is the nominal diameter of the core and capital D is the nominal overall diameter of cryostat of the HTS cable. Three short cores were bent around a test cylinder which was simulated of steel drum. The test condition is ambient temperature and at least one complete turn and unwound without axial rotation. The test core was rotated through 180 degrees and bending process repeated 3 times in each bending diameter. Before preforming the bending test, we measured the critical current at 77K and self-field. After finishing the bend test, the critical current was also measured again and its results compared with previous results. To follow Cigre TB538, degradation of the critical current should be under 5%, definitely. Figure 2 shows the
photo of the wooden frame and the short core bend for the test. Also, Figure 3 shows the experimental results before and after the bending test among three cores. It means that no degradation of the critical current at 77.3 K temperature was found. These results could be applied to determine steel drum diameter for manufacturing and delivery of AC 23kV HTS cable.

**Table 4. The Diameter of Bending Test.**

| Item         | Unit | Value                |
|--------------|------|----------------------|
| Single Core  | -    | 25(d+D) + 5%         |
| Three Core   | -    | 20(d+D) + 5%         |

**Figure 2. The Wooden Frame for the Bending Test.**

**After Bending Test, Measurement of DC Ic**

**Figure 3.** Before and After Bending Test, Measurement of DC Ic.
2.3. FEM Simulation for AC Loss Calculation

One of FEM simulation results in conducting layer was shown in Figure 4. This result shows an influence of the magnetic field to itself and adjacent the HTS wires. The magnetic flux distortion at edge was occurred because of gap distance between adjacent HTS wires. As the gap distance decreases, the magnetic field becomes parallel magnetic field. These characteristics were occurred in every superconducting layer. Thus, beneficial way of reducing AC loss should be made small gap distance because magnetic field at the edge of the HTS wire should be made parallel magnetic flux as possible as [3]. Dot circle in Figure 4 well explains above phenomenon. Figure 4 shows that distortion of magnetic field by the gap distance. Furthermore, this characteristic reduces the critical current of the HTS wires because this arrangement of the HTS wires is generally occurring leakage magnetic field in each layer. During the superconducting operation, AC loss in the HTS cable will be generated due to the magnetic field in radial direction which is a perpendicular field of the REBCO layer. Moreover, AC loss will be changed by current distribution of each layer. Those two simulation processes which were calculated AC loss and current distribution were repeated to satisfy cooling capacity of cryo-cooler and engineering design goals.

![Contour Plot of HTS wire](image)

**Figure 4.** Magnetic Calculation of HTS wire for AC Loss.

2.4. Measurement of AC Loss

Based on above design process, three short cores manufactured and experiments AC loss measurement as Figure 5. To measure AC loss, we used an electrical method with cancelation coil. Actually, voltage and current are 90 degrees shifted in AC. The voltage signal from the HTS cable was measured by cancelling the inductive voltage component. To make same phase between voltage and current, the cancellation coil could be used and its configuration could be controlled such as number of coil turns and diameter of coil. Thus, phase shift was controlled by a cancelation coil [6].

Critical current of conducting layer at Core #2 is the lowest of among three short cores. Thus, measurement AC loss of Core #2 is the highest compared with the other cores. AC loss of the Core #1 and Core #3 were similar and measured value was approximately 0.18 W/m/phase at rated current. These results mean that the HTS wire with higher critical current should be arranged at conducting layer to reduce AC loss.
2.5. Short Circuit Test

The fault current will be bypassing to copper during the fault condition. The fault level of distribution in South Korea is 25 kA for 0.5 second which means the HTS cable should be withstood the maximum fault level. Preparation of the circuit test is shown in Figure 6 and the fault current is going through instant three phases and end of three phases are connection as common. This test method is the most sever experimental condition of circuit test of Core #1. Several thermal couples are attached at former surface to measure the rising temperature during the fault current loading. Figure 7 shows experimental results. The increased temperature of the HTS cable during fault condition is 18 K. These results are compared with boiling temperature of LN$_2$ at pressure status of outlet of the HTS cable. Estimated pressure at the outlet of the cable is 6.7 bar(g) and boiling temperature at this pressure of LN2 is approximately 98.5 K. Thus, the maximum raising temperature of the HTS cable during the fault is under 92.8 K. The HTS cable will be able to withstand the its fault condition because the increased maximum temperature was less than boiling point temperature of LN$_2$ at pressure of the outlet of the HTS cable.
3. Type Test and Prequalification Quality Test of 23kV 50MVA HTS Cable
For investigating AC 23kV 50MVA HTS cable, the bending test, AC loss, DC Ic and short circuit tests with short sample cable were conducted based on Cigre TB538 and KEPCO standard [5]. For performing the type test, sequence of the whole test is well explained in Table 4. The bending test will be also conducted as the routine test before the HTS cable shipment. Generally, gaseous nitrogen could be used the pressure test because it can easy flow and apply pressure. The one cycle of load cycle test spends 24 hours and the HTS cable will experience 20 cycles. During the test, rated current for 8 hours per cycle was applied the HTS cable. After finish the type test, 2 times repeated cool-down and warm-up as thermal cycle are going to progress as prequalification quality (PQ) test due to induce huge thermal shock. The HTS cable will be experienced mechanical stress during the thermal cycles. From the previous test, it found that moved HTS cable by thermal contraction force was saturated within 3 cycles of the thermal cycle. Thus, total number of repeated thermal cycle is 3 cycles as PQ test during the whole test. Figure 8 shows the schematic sketch for the type test of AC 23kV 50MVA class HTS cable system including the cable, the return pipe and the accessories.

Table 5. Specifications of Type Test.

| Item                  | Value                                      |
|-----------------------|--------------------------------------------|
| Bending Test          | 3 times                                    |
|                       | 20(d+D) + 5% = 3,613 mm + 5%               |
| Pressure Test         | 30 min.                                    |
|                       | 13.2 bar(g) (Gaseous Nitrogen)             |
| Pressure Drop Test    | -                                          |
|                       | Cable ≤2.5 mbar/m                          |
| Load Cycle            | 2.0Uo 8.0hr                                |
|                       | 27kV / Current : 1,760 Apeak               |
| Impulse Voltage       | Positive                                   |
|                       | 10 times : + 150 kV                       |
|                       | Negative                                   |
|                       | 10 times : - 150 kV                       |
| AC Voltage            | 2.5Uo                                      |
|                       | 33 kV                                      |
| Thermal Cycle         | 2 times                                    |
|                       | Repeated Cool-down and Warm-up             |
4. Type Test and Prequalification Quality Test of 23kV 50MVA HTS Cable

The preliminary tests and FEM simulation were investigated to verify design of the HTS cable. LS C&S was make three kinds of short cores according to critical current at 77.3 K. The experimental test of Measurement value of AC loss was under 0.6 W/m at rated current. Also, no degradation of critical current by bending test at diameter of 2,500 mm was found. The increased maximum temperature during the fault condition was approximately 18 K which means that pressure can suppress LN2 to avoid bubbling at transient current condition. Based on above experimental and design results, LS C&S plan to make AC 23kV 50MVA class HTS cable and return pipe for circulation of LN2. The return pipe has been already manufactured, and the manufacturing HTS cable will be finished until second quarter of next year. The type test and PQ test will be finished until third quarter of next year.

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