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

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Abstract. As an initial step of this innovation, in September of 2016, KEPCO (Korea Power Electric Corporation) has launched the world first commercial superconducting cable project, named SSS (Superconducting Smart platform Station in South Korea) project, which will be not only the first commercial trial in the grid but also a test bed for Smart Superconducting Platform in South Korea. The main target design of this project is installation of 23kV 50MVA class HTS cable a system in the power grid. Type of this HTS cable is 3 phases in One Cryostat which is a remarkable way to transfer large power with low voltage and no electric magnetic field that means prevention of heating of other cores of phases and two metal sheaths of the cable. Total length of HTS cable between ShinGal and HeungDuk substations is slightly over 1km and it has 2 sets of normal joint box and 2 sets of termination. In this HTS cable system, a mechanical stress during the cool-down and warm-up is a major issue for increasing stability to set-up the HTS cable system and to connect existing power lines. To solve this issue of SSS project, we developed a simulation program which used Equivalent Solving Method for reducing and predicting thermal contraction force of the HTS cable under the mechanical stress. Also, mechanical strengths of metal sheaths, that made of aluminium material and the former that was stranded of copper wires was measured by the tensile tests. Coefficient of elasticity and thermal expansion according to various temperatures was calculated by the experimental data. And then, the analytical method was applied to verify installation method by approximate 40m length HTS cable that has various installation conditions such as vertical shape, often called snake method, at straight route in installation path. From the above procedures, we find that mechanical strength of each component of the HTS cable can calculate according to installation route in the power grid.

1. Introduction
Superconducting applications such as a HTS cable, an HTS motor and SFCL for power grid is state-of-the-art technology [1]. Especially, HTS cables can transfer large electrical power source with low losses and are expected to be not only environmental applications but also electromagnetic interference free performance which means no influence adjusting other cables. It has a compact size compared with conventional power apparatus. However, these apparatuses are also considering that are being well-fit and connection of existing applications in the power grid. Thus, various R&D projects were performed and demonstrations were being promoted in the world.

Figure 1 shows the case study for the replacement of conventional cable and the installation method of an additional HTS cable in a tunnel in the grid. This way can make more stable power grid and save cost for transferring power source than existing only installation conventional cables because one...
circuit of HTS cables can flow over 5 times power higher than one circuit of a high voltage conventional cable and utilize empty duct line in tunnel. Thus, HTS cable is value-creating product and powerful solution to be able to change existing power apparatus.

Since 2001, Korea Power Electric Cooperation (KEPCO), LS Cable&System (LS C&S) and various institutes have been cooperated 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 the DAPAS program, a basic design concept of distribution and transmission level HTS cable system was established. The HTS cables were manufactured for the short length cable tests and the type test to verify our design factor for applying power gird. The HTS cable in the distribution grid of 23kV class line voltage in South Korea can transfer the bulk power capacity like conventional cable in transmission level which means the HTS cable can replace the existing conventional transmission cable and save cost of civil work to install extra cable in the power grid. Thus, KEPCO and LS C&S installed 23kV 50MVA class HTS cable in the Icheon substation and operated for 20 months. Total length and configuration of this HTS cable are approximately 500m with 2 sets of outdoor termination, 1 set of normal joint-box and the 3 Phase-in-One cryostat type, respectively. During 20 months, unmanned operation in the power grid was for 18 months. The next step of this project is increasing power transmission capacity as 23kV 120MVA. In case of this HTS cable, the installation route is approximately 100 meters. The cable includes 2 sets of out-door termination and type of cooling system is decompression unit which is compact type by putting all components in the container. These demonstration schedules and projects are called Green Superconducting Electric Power Network at the Icheon Substation (GENI). Based on experience and results from DAPAS and GENI program, KEPCO made the world first commercial HTS cable project for Superconducting Smart Platform in South Korea. Construction of the cooling system including a turbo brayton type croyo-cooler and cryogenic pipe was already started to install in HeungDuk substation. Power capacity of this project is 23kV 50MVA class and HTS wires are 2nd generation type. 3 Phase-in-One type of HTS cable of 1,035 meters will be manufactured to transfer electrical power between ShinGal and HeungDuk substations.

2. Preliminary Test
Firstly, to gain the mechanical properties of aluminium metal sheath and the copper stranding former, tensile tests were performed at room-temperature (RT) and 77.3 K cryogenic condition. These experimental results should be applied basic input data for investigating FEM simulation program that estimated thermal contraction forces during cool-down and warm-up. This is first step to be increasing
stability and accuracy of the simulation program. Finally, approximately 50 meter cable was installed to confirm simulation program.

2.1. Tensile Test for Metal Sheath

The mechanical property of an HTS cable can be changed cross-section of the area of each component such as former, 1st and 2nd metal sheaths. However, thermal contraction force of the 2nd metal sheath is very small because temperature difference between inside and outside is almost zero. The measured tension tests of values of former and the 1st metal sheath in the straight line are 2.01 tons and 1.58 tons, respectively. The length of the testing sample of the former is 1,420 mm at RT. The ratio of the shrinking length of former by cool-down process until 77.3 K is 0.29% compared the original length of the former. The saturated time until 77.3 K of 1st metal sheath is only 15 minutes. Fig. 2 shows the experimental configuration for the tension to gain the mechanical properties of the former and metal sheath at RT and 77.3 K. These experimental results were applied to adjust input data of FEM simulation for increasing accuracy.

![Fig. 2. Tensile Tests at RT and 77.3K.](image)

2.2. Tensile Test for Pulling Eye

To connect the HTS cable to the winch, pulling eye is needed. Configuration of the pulling eye consists of hook for connecting winch and pressing area for connecting the copper former. In general, installation tension is approximately less than 2.0 tons. Thus, tension strength of the pulling eye should be performed according to the inner diameter of various hooks and the length of pressing area. Fig. 3

![Fig. 3. Tensile Test for Pulling Eye at RT.](image)
shows experimental set-up and the results of the after tensile tests of the pulling eye with the hook of 30.0 mm inner diameter and the pressing length of 25.5 mm, respectively. Before the tensile test as Fig. 3(a), the pulling eye was so close the core. As Fig. 3(b) shown, the former, made of the round shape of the copper strand, was stretched by the force of the longitudinal direction. The yield strength of the experimental case is approximately 4.5 tons and breaking strength is approximately 5.2 tons. Furthermore, the 1st and 2nd metal sheath was welded to pulling eye after manufacturing the HTS cable. In general, after the welding process, the yield strength will be increased more than only pressing with the former.

2.3. Electromagnetic Force during the Transient Status
Electromagnetic force will be generated in this 1st metal sheath during the fault condition because the HTS wires at the shield layer are experienced to quench status. The pressure condition of the HTS cable is 8.5 bars and the electromagnetic force of vertical direction is 18.51 kg/cm, respectively. Table 1 shows the specifications of the aluminium metal sheath for the FEM simulation. Based on the above status, possible thickness of aluminium metal sheath should be calculated by FEM simulation to confirm the structural feasibility during the fault. The input values, which were gained by the tension tests, for simulation of aluminium sheath strength are modulus of elasticity, yield stress and tensile stress. Each value at RT is 70 GPa, 43 MPa and 72 MPa, respectively. Generally, these properties are increasing at cryogenic condition. Thus, the measurement at RT is the worst condition. Based on FEM simulation of effective stress according to various thicknesses of metal sheath, suitable aluminium thickness of 1st metal sheath is 3.0 mm then safety margin against for electromagnetic force is over 1.2 times during the fault.

| Item            | Value  |
|-----------------|--------|
| Inner Diameter  | 83.3 mm|
| Wave Height     | 4.4 mm |
| Pitch           | 28.0 mm|
| Average Thickness | 3.0 mm|
| Outer Diameter  | 98.1 mm|

Table 1. The Specifications of the 1st Aluminium Metal Sheath.

![Figure 4](image-url)  
(a) Modelling for FEM simulation  
(b) The FEM simulation result

**Figure 4.** Effective Stress according to Aluminium Sheath Thickness.
3. Installation Design for 23kV 50MVA HTS Cable
The total length of an installation route is approximately 1,035 meter, including 2 sets of the normal joint box, 2 sets of outdoor termination and the return pipe for the LN$_2$ circulation are prepared to install the HTS cable system into the power grid. Table 2 shows the installation route of 23kV 50MVA class HTS cable and return pipe. During performing the installation process, there are five bending areas including one pass-manhole (P/M) as an off-set area and two manholes for normal joint box (N/J). Diameter of each bending point is less than 11.0 meters, which means that the HTS cable isn’t receive any damage form the installation. For installing the 1,040 meter HTS cable and return pipe, the steel drum would be set on the under roller (U/R) at the ShinGal substation and N/J #1 or N/J #2. Then it is pulled into the duct and tunnel from the ground section by a winch and scaffold. Figure 5 shows that installation route of 23kV 50MVA class HTS cable between HeungDuk and ShinGal substations. Initial R means bending area where the HTS cable would be moving to the center point of the bending area owing to the thermal contraction force. The pulling eye for connecting the winch should be the pressed of copper former and welding the 1st and the 2nd metal sheaths, respectively.

Generally, installation method was divided to 3 cases by considering route condition. Table 3 shows case studies of installation method. The case #1 is a fixed termination type which is the best way to connect the existing power cable in the power grid. However, the whole thermal contraction force should be absorbed by the HTS cable, the joint box, and the cleat. The case #2 is a free sliding method which means the termination is freely moving in the longitudinal direction of the thermal contraction force. There is limitation to move the termination at the substation and also check the moving effect of reducing the fore. The case #3 is an applicable method by considering route condition. For applying the snake method, the substation has enough to straight line to set-up steel frame for making wave shape of the HTS cable. As increasing the cleat stroke, the thermal contraction force could be absorbed by the cleat. It has limitation to absorb whole force. Thus, the case #3 also considers sliding the termination but it constrains the moving length of the termination.

| Table 2. Installation Route of 23kV 50MVA HTS Cable and Return Pipe. |
|-----------------------------|-------------------------------|
| Item                        | Value                         |
| Installation Route          | 1,035 m                       |
| Normal Joint Box (NJ)       | 2 sets                        |
| Termination                 | 2 sets                        |
| Manhole / Pass-Manhole (P/M)| two / one                     |
| Cable Type                  | 3 Phase-in-One Cryostat       |
| Return Pipe for LN$_2$      | Yes                           |

| Table 3. Case Studies of Installation Method. |
|-----------------------------------------------|
| Case Study                    | Contents                                    |
| 1 Fixed Termination            | Severe Condition                            |
| 2 Free slide of Termination    | Checking Sliding Effect at Termination       |
| 3 Free Slide + Up to Cleat Stroke Up | Reduce Reaction Force by the Thermal Contraction |

3.1. Tensile Test for Pulling Eye
A metal structure should be considered to withstand the HTS cable weight, including LN$_2$ and the thermal contraction force during the cool-down and the warm-up. The angle support is considered to static force in normal operation and transient force during the fault. The hanger structure is also
considered to weight per unit area against the weight of HTS cable. Fig. 6 shows the metal structure in the tunnel, which consists of the angle support, hanger and bolt.

3.2. Installation Design for HTS Cable

For the installation 1,035 meter HTS cable and return pipe for LN$_2$ circulation, total number of the steel drum is three for cable and two for return pipe. To follow local regulation, maximum diameter of HTS cable is less than 153.0 mm because the inner diameter of corrugated hard polyethylene (ELP) pipe is 200.0 mm. The main role of the ELP pipe is protecting cable in duct and the power cable is installed in the ELP pipe. After the installation, DC or AC voltage test shall be performed to check damage of the overs-heath of the HTS cable during the installation. Advanced verifications for stable installation are following below:

Table 3 shows specifications and check points of the bobbin test and mini cable test to keep the stability of the HTS cable before the installation. The rod type metal material can be applied the continuity test to check duct status then the mini cable is passing the available duct. The mini cable has similar or same diameter compared with actual the HTS cable to install in the duct.

- Advanced verifications for the installation of the HTS cable
  1) The Bobbin Test and The Mini Cable (Piece) Test
     - For checking duct condition by the bobbin
     - The feasibility test for installation with same diameter of the HTS cable piece
  2) Communication with Main Operator
     - The main operator control the whole system by control box and order to drive the winch
  3) Pre-Installed cleat and metal structure at the ground and the tunnel
  4) Checking the tension by a tension meter during the installation

![Figure 5. Installation Path of the HTS Cable and the Return Pipe for the circulation of LN$_2$.](image-url)
Case Studies for Installation

1) Case #1, Fixed Termination
   : Increasing thermal contraction force to 450 kgf until R3 bending point
   : However, average force approximate 180 kgf/m²
2) Case #2, Sliding Termination
   : Movement length of the termination is less than 150 mm
   : Increasing the force of sliding cleat at bending point of R2 and R3
3) Case #3, Sliding Termination and Increasing Cleat Stroke
   : In the case of the free sliding at P/M, thermal contraction force is less than 300kgf
   : The termination movement is less than 300 mm, the contact force approximate 500kgf/m²

| Item                          | Value                  |
|-------------------------------|------------------------|
| **Short Length and Dia. of The Bobbin** | 600.0 mm and Ø164.0 mm |
| Specifications               | No crush and dent      |
| Check Point                  | Every duct             |
| **Short Length and Dia. of Mini Cable** | 6.0 m and Ø153.0 mm   |
| Specifications               | No twist and damage    |
| Check Point                  | Pass the bobbin test   |

Based on the case studies from the FEM simulation, the suitable installation method can be chosen for reducing the thermal contraction force during the cool-down and the warm-up. The case #3 with the snake method in straight section near the each substation area, increasing the cleat stroke, and the limitation moving the length of the termination is applicable way to be stable and reducing the thermal contraction force of the HTS cable.

4. Discussion and Summary
For increasing stability and safety of the HTS cable during the installation, various preliminary tests were conducted to gain the mechanical strength of each component of HTS cable such as the copper...
former, the 1\textsuperscript{st} and the 2\textsuperscript{nd} metal sheath. From the experimental results, the FEM simulation program made to calculate the electromagnetic force according to various thickness of the aluminium metal sheath and choose the installation method between HeungDuk and ShinGal substations. The snake installation method is best way to absorb thermal contraction force during the cool-down and the warm-up. However, the straight section near the both substations is not enough to reduce the thermal force. In this case, the sliding termination and increasing cleat stroke can be applied the method by basing on the FEM simulation results.

References

[1] Ryu Kang-Sik, Jo Young-Sik and Park Minwon 2006 Overview of the development of the advanced power system by the applied superconductivity technologies program in Korea

*Supercond. Sci. Technol.* **19** (3) S102–S108