DEVELOPMENT AND DEMONSTRATION OF THE 3-IN-ONE™ HIGH TEMPERATURE SUPERCONDUCTING POWER CABLE

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ABSTRACT

Sumitomo has developed and installed two HTS cable systems in Korea and in Albany NY. The cable in Korea has specifications of 22.9 kV and 1250A capacity with 100m length. It was installed at the KEPCO test site and tested at the nominal voltage and current as commissioning tests, successfully. Sumitomo also installed a 34.5kV-800A-350m HTS cable in Albany, NY incorporated with SuperPower Inc., National Grid, the BOC Group, successfully. It has been connected to the real grid and operated since July 20th in 2006.

INTRODUCTION

Since 1988, when BSCCO HTS material was discovered in Japan, Sumitomo Electric Industries, Ltd. has been developing the BSCCO wire for real applicable HTS wire. The recently developed CT-OP™ (controlled over pressure) process made it possible that the wire has extreme characteristics for practical use. The innovation of the Bi-based wire is the turning point for the HTS application to the real application for its user-friendly characteristics.

MERIT OF HTS CABLE

The features and advantages of HTS cables are classified into three general categories: economical, environmental and life-time / reliability.

Economical advantages

HTS cables achieve large power transmission capacity and low power loss in a compact size. This is effective in reducing the costs of cable system construction and operation. It also allows low-voltage, large-current use, and compared with conventional super high-voltage power cable. Therefore, it has advantage to acquire the right of way for a new transmission line because of transmitting at lower voltage with no objection by the residents.

Environmental advantages

The application of HTS cables is also effective in reducing CO_2 emissions. HTS cables also achieve reduced energy consumption by reducing power transmission loss, as well as conserving resources through the effective use of existing equipment. In addition, the cables do not use insulation fluid, as is used in conventional oil-filled (OF) cables. The liquid nitrogen that is used as a coolant serves as an insulating material, resulting in cables that are non-flammable and non-explosive in nature. The HTS cables are also EMI-free, meaning that it doesn't leak the magnetic or electrical field because of its superconducting shield.

Advantage of service life / reliability

The primary factors of degradation in the case of conventional cables are repeated expansion and contraction of the cable itself due to changes in temperature throughout the day and the year, and thermo-chemical and electrical degradation due to temperature rise. The temperature of HTS cables is kept generally constant at an extremely low temperature of approximately -200 degree Celsius by the liquid nitrogen, so there is no thermo−chemical or thermo−mechanical aging over time.

The HTS cable is composed of electrical insulation of insulating tapes, Polypropylene Laminated Paper (PPLP®), impregnated with liquid nitrogen. The liquid nitrogen has an electrical strength similar to that of the synthetic oil that impregnates the insulating paper in the OF cable and it offers HTS cable has the insulation performance equivalent to the PPLP-OF cable. Based on the results of long-term voltage endurance properties under partial discharge stress in the liquid nitrogen (V-t test), V-t performance equivalent to PPLP-OF cable was obtained and it is reflecting the insulation design of the HTS cable[1)].

3-IN-ONE HTS CABLE

Sumitomo has been developing HTS cable with 3-in-One type [2)], which means that three cable cores in one cryostat as shown in Figure 1. A superconducting conductor is wound with BSCCO wire on the former, spirally. For electrical insulation, PPLP is wound on the conductor. When it is cooled with liquid nitrogen, liquid nitrogen is immersed into the insulation paper of PPLP. For canceling the magnetic field caused by conductor current, BSCCO wires are also wound on the electrical insulation as a superconducting shield. As a protection against short circuit current, the shielding employs a wound copper tape. The three cable cores are stranded and housed in a cryostat. To reduce the tension caused by thermal contraction from room temperature to liquid nitrogen temperature, the three cores are stranded with some slack in three cores. The cryostat is composed of a stainless steel double-wall corrugated pipe and an insulator. The space between inner and outer pipes is vacuumed to reduce the heat invasion from the outside. Some tension members are attached on the cryostat in case of installation with a big tension.

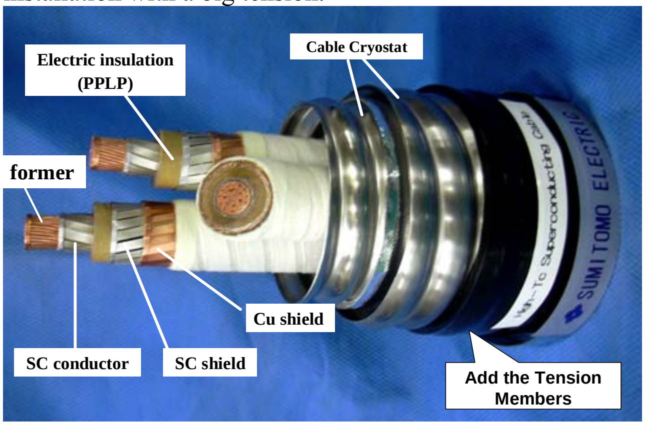

Figure 1 Structure of a 3-in-One HTS Cable

Sumitomo Electric has recently joined two big HTS cable project in Korea and in USA. Both cables were already installed and operated at each site.

KEPCO PROJECT

Project Background

Electric energy consumption in Korea increased significantly from 2001 to 2004, at an average annual growth rate of around 5 %, especially, the growth is focused in the Seoul area[3)]. On the other hand, the deployment of power transmission and distribution lines in the metropolitan area has not been progressed because of not enough space for new cable or difficulty to get the right-of-way. One solution anticipated to resolve this problem lies in superconducting cable technology, which allows cables that are the same size as conventional products to transfer much larger quantities of electricity.

As a case study on the practical application of superconducting technology, the Korea Electric Power Corporation (KEPCO) is planning to conduct research on the operation method of superconducting cables if they are put into practice, assuming a voltage of 22.9 kV, which is the power distribution level in Korea; a current of 1,250 A, which is five times the standard capacity of 250 A; and cables that can be installed in underground ducts with φ175 mm in urban areas[4)].

System specifications and configuration

Figure 2 and Table 2 show the system configuration and the specifications, respectively. Sumitomo Electric manufactured and installed all of the components, such as a HTS cable, two terminations, a cooling system and so on. The cable was installed along a route combining tunnels and ducts with the terminations being installed at the two ends of the cable. The system is cooled with the sub-cooled liquid nitrogen, which is sent to the cable system, and after cooling each part, returned from the remote termination to the origin via a return pipe. Figure 3 shows the cable installed in the tunnel.

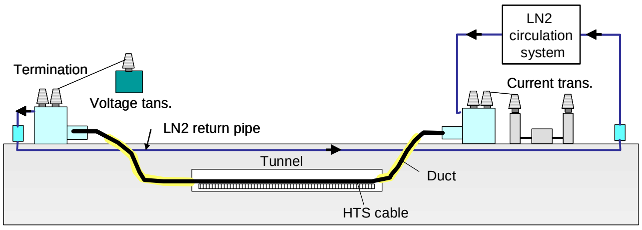

Figure 2 System Configuration

Table 2 Cable System Specifications

Item	Specifications
Rated voltage	22.9 kV
Rated current	1,250 A
Rated capacity	28.6 MVA
Cable type	Three-in-one superconducting cable
Length	100 m
Electrical insulation	Low temperature dielectric
Termination	EB-A x 2 units
Installation	Tunnel + duct (30m)
Cooling system	Liquid nitrogen circulation

Figure 3: Schematic view of the KEPRI cable system

Cooling and commissioning tests

Initial cooling was carried out on-site. It took about two days after the start of initial cooling to cool the entire length of the cable to the liquid nitrogen temperature. After initial cooling was completed, circulation cooling by liquid nitrogen was started, and each element test was carried out individually.

A critical current (Ic) was measured for the conductor of each phase at liquid nitrogen temperature 72 K. The measured Ic was around 2350A, defined by a criterion of 1 μV/cm., for each phase as is shown in figure 4. They are in good agreement with the predictions made from the results of Ic 1800A, at 77 K in the shipping tests. As the result, it is concluded that the conductors did not deteriorate during the processes of manufacturing, transportation, installation, assembly, and cooling.

A single-phase voltage was applied while shorting the high voltage portion of a three-phase cable. The testing

voltage value was 33 kV, which was designated by KEPCO (using the withstand voltage of the IEC 22 kV-class cable after installation as reference), and this was applied for five minutes, successfully.
After confirmation of the cable performance with above tests, the acceptance test was conducted at 13.2 kV (voltage to ground) and a current of 1,250 A for 48 hours, successfully.
KEPCO is now planning to conduct technical and economic assessment of the cable through various tests including long-term operation tests and heat cycle tests.

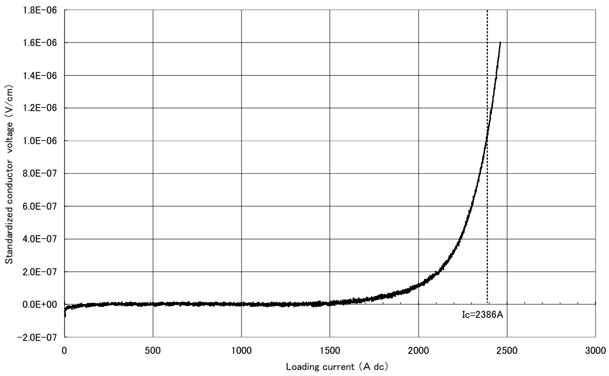

Figure 4 Conductor Ic Measurement Result

ALBANY PROJECT

Overview of the project

In the United States, the fragility of the power grid has been shown as a major problem -- for example, it was pointed out as a factor in the massive blackout that occurred in New York in August 2003 -- and strengthening the power grid is considered an urgent issue. In the Energy Policy Act enacted in August 2005, upgrading of the power transmission grid was ranked as an issue of vital national importance. One of the solutions for this problem is the "Grid 2030" plan, to construct a strong nationwide power transmission grid made up of HTS cables by 2030[5)].
An HTS cable demonstration projects have been conducted on an actual power grid of National Grid Company in Albany NY, funded by the Department of Energy[6)]. The rated voltage, current and capacity of this power line are 34.5 kV, 800 A, and 48 MVA, respectively. The cable was installed in 350 meters underground conduit with an inner diameter of 6 inches. The world's first cable-to-cable joint was placed inside a vault, and both ends of the cable were connected to overhead power transmission lines. The cables, joint and terminations were in conformance with, respectively, AEIC standard C55-94, IEEE standard 404 and IEEE standard 48.

Installation

Figure 5 shows the route profile for the HTS cable installation. The 320 meter cable section has a 90° bend with a radius of 12 meters and the maximum difference in elevation of approximately 5 meters.

The cable was pulled into the long duct with the same method as is commonly used for conventional cables. The maximum tension was approximately 2 tons which was almost same as the calculated one with friction coefficient of 0.25 in advance.
After the cable installation was completed, it was confirmed that there was no abnormal elongation or external damage to the HTS cable, and there were no leakage in the vacuum level of the HTS cable. It is added that the cable cryostat was vacuumed entirely and sealed off before shipping with no re-vacuuming at the site.

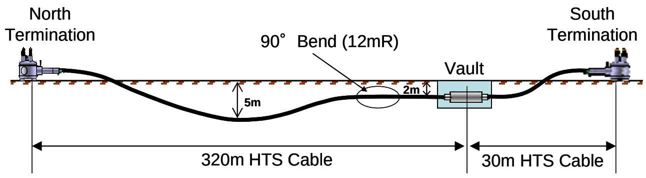

Figure 5 Profile of Cable Installation Route

Figure 6 shows a schematic view of the HTS cable-to-cable joint. This structure comprised the connection of a former, connection of the HTS conductor, formation of a supplementary insulation layer, and connection of the HTS shield and Cu shield layer. The core joint was not fixed to the case (ground), and an allowance was provided inside the case to accommodate core behavior. The vacuum thermal insulation case assembled on the outside of the cable core joint is separated from the cable cryostat. Finally, waterproof and corrosion-proof treatments were conducted. Figure 7 shows the joint in vault after construction.

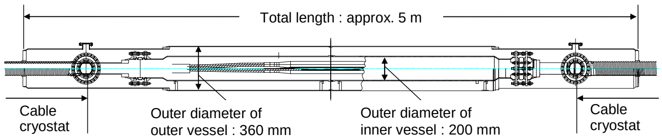

Figure 6 Schematic view of "3-in-One" HTS Joint

Figure 7 HTS Joint in Underground Vault

The termination had a "3-in-One" structure which means that 3-cores connections and 3-phase bushing are housed in one vessel. At the introductory part of termination vessel, 3-cores were connected with the central conductors of the three epoxy units fixed to the case and supplementary insulation was formed, and the shield layers for each phase were connected in the shape of 3-phase short-circuit to generate the induction current. The high voltage part covered with the porcelain was lead out from the vessel via current leads inside the bushings. After assembling the termination, the termination vessel was fixed to the ground. Figure 8 shows the HTS termination after assembling was completed.

Figure 8 Termination at the Albany site

Commissioning test

After cooled with liquid nitrogen completely, some measurements and tests were conducted as the commissioning test.

The critical current measurements were conducted for each phase conductor at a average cable temperature of 73 K. The Ic was 2300 A, defined as 1μV/cm, for all three phases, which closely matches the value expected from the results of the sample test at 77 K of 1800 A.

The heat invasion into the cable system in no-load condition was measured. The heat loss in the 350-meter HTS cable section (including the joint section) is 1.0 kW, which was almost same as the designed value. In addition, the total heat loss throughout the entire HTS cable system including both terminations, the return pipe and the pipes connecting to the cooling system was 3.1 kW, that is also approximately same as the designed value of 3.0 kW.

The pressure drop in the 350-meter cable section under the conditions of a liquid nitrogen flow rate of 50 L/minute was 0.075 MPa. This value closely matched with the design value of 0.07 MPa for a duct friction coefficient of 0.08, confirming the validity of the design.

As the final test, a DC withstand voltage test was conducted at DC 100kV for 5 minutes successfully in conformity to the AEIC standard.

In-Grid Operation

From the results of tests and measurements above, it was concluded that the cable system has good performance for in-grid operation. The cable was connected to the actual grid by National Grid on July 20th. From that time, it has been operated for more than six months stably.

The operating status of the HTS cable system is monitored for 24 hours a day by the Remote Operation Center (ROC) in The BOC Group. The operating status can also be monitored in real time from anywhere around the world via the internet. In addition, the temperature, pressure and other operating conditions of cooling system can be fine-adjusted by remote operation. This system enables unattended operation at the Albany site.

Figure 9 shows the recent status of cable temperatures and transmitted electricity in the HTS cable. Transmitted electricity has been very variable but the temperatures have been very stable. On November 12th, the cable experienced the first fault current of 7 kA in 8 cycles. At that time, the breaker was operated normally and the operation was suspended. After deliberate checking the cable, no damage on the cable or the system was found and then the operation was restarted.

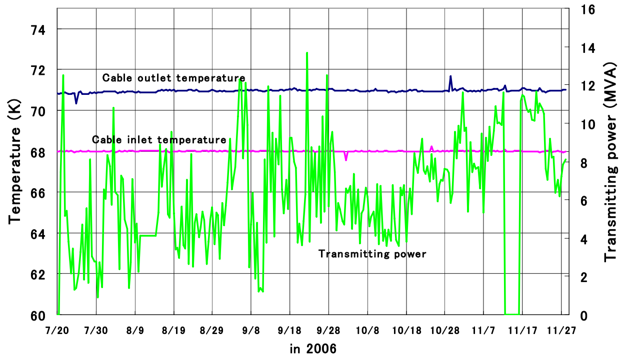

Figure 9 Albany cable operation statuses

CONCLUSION

Sumitomo joined recently two HTS cable project in Korea and the USA. Both cables have been installed and operated successfully. Especially, the Albany cable has been operating in the real grid and much information or data is now being accumulated. These data can clarify that the HTS cable has enough reliability and stability to use for real power grid and be enable the HTS cable to be commercialized in near future.

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