Testing and Demonstration Results of the 350m Long HTS Cable System Installed in Albany, NY

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Abstract— The Albany Cable Project team (BOC, National Grid, Sumitomo Electric, SuperPower) have built and tested a 350-m long HTS cable and cryogenic system rated at 48 MVA (800A$_{rms}$, 34.5-kV). The cable system included the world's first demonstration of an HTS cable-to-cable joint (or splice) as well as some novel design aspects in both the cryogenic refrigeration system and the terminations. The cable was installed and began operation in July 2006. This paper will summarize the testing and operational aspects of the HTS cable system and its integration into the existing National Grid 34.5-kV network.

Index Terms— Cryogenic Refrigeration Systems, High Temperature Superconductors, HTS Cables, Superconducting Cables

I. INTRODUCTION

Arguably three of the most important considerations that electric utility personnel must consider in evaluating and introducing new technologies into their existing networks are: the overall reliability of the technology and its support systems, the impact that the new technology will have on the existing network; and what the relative cost/benefit analysis looks like compared to other available technologies.

To prove the feasibility and reliability of underground HTS cables, demonstration projects have been planned and executed around the world. In the United States there are currently three such demonstration projects underway [1][2][3]. Although these projects have widely varying performance characteristics, such as operating voltage & current levels, they all have a common underlying goal to address the fundamental questions of how HTS cables will perform in a typical utility setting.

The Albany Cable Project (ACP) is a collaborative effort between SuperPower (prime contractor/2G wire supplier), Sumitomo Electric Industries (HTS cable manufacturing, installation and testing/BSCCO wire supplier), The BOC Group (Cryogenic refrigeration System (CRS)/ system monitoring), and National Grid (host utility/system protection). The program is funded by a combination of the aforementioned industrial partners, the Department of Energy (DOE) through its SPI program and the New York State Energy Research and Development Authority (NYSERDA).

The cable system that has been installed operates at 34.5 kV and has a nominal current carrying capacity of 800 Amperes. The total length of the cable from end to end is 350 meters comprising of two sections; one 320m long and one 30 m long. The two cable sections were pulled into underground ducts using conventional cable pulling techniques and they were then joined together in an underground vault [4]. The joining of two independent cable sections is important to show that lengths of HTS cable can be connected together to make a long cable installation possible.

The first phase of the ACP consists of two HTS cable sections made with SEI's CT-OP BSCCO wire[4]; a 350m long return pipe, and the BOC designed CRS. A follow-on phase of the program will replace the 30m BSCCO cable section with an equivalent length cable made from YBCO wire fabricated by SuperPower. Following the installation of the cable system, a series of pre-energization testing was completed to verify its performance and that all back-up systems were working properly. Phase 1 of the ACP went into operation on the grid on July 20, 2006. There have been no interruptions in service since the cable went online and stable operation has been maintained throughout.

This paper describes the results of the pre-energization testing and looks at the impact on load flows when an HTS cable of various lengths is installed in part of National Grid's 34.5 kV network in Albany, NY.

II. CRYOGENIC REFRIGERATION SYSTEM

A. *Refrigeration Arrangement*

The Albany Cryogenic Refrigeration System (CRS) employs a hybrid arrangement that accepts refrigeration from

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either a cryocooler or bulk liquid nitrogen. As shown in Fig. 1, the skid mounted CRS consists of a cold box housing a thermosyhon and liquid nitrogen pumps. The pumps circulate subcooled liquid nitrogen in a closed loop to the HTS cable. The thermosyphon accepts refrigeration from either the primary cryocooler, or a backup bulk liquid nitrogen and vacuum blower combination. The CRS is also designed to provide cold nitrogen gas at any temperature and flow rate for the initial cable cooldown.

Fig. 1. Cryogenic Refrigeration System. Hybrid refrigeration arrangement using interchangeable cryocoolers and back-up liquid nitrogen.

The CRS design incorporates cost effective and reliable back-up of all key components in the event of failure. The primary back-up mechanism is bulk liquid nitrogen/vacuum blower operation in the event of cryocooler failure. In addition the pumps, all key instruments, and control loops have back-up provisions.

B. *System Testing*

The CRS was tested extensively prior to cable installation as reported earlier [5][6]. Following cable installation and cooldown, the CRS was put through a series of performance tests which included confirmation of the various back-up systems.

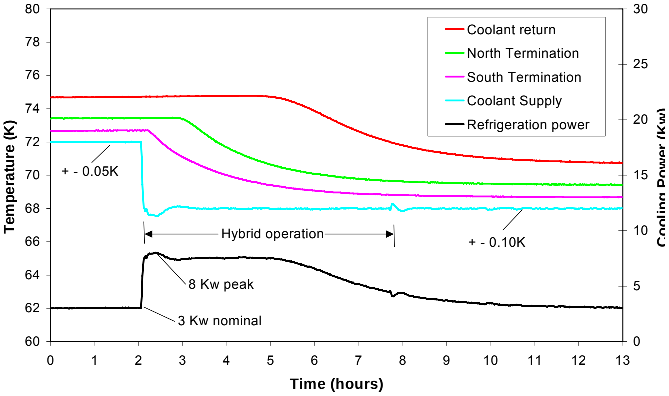

Fig. 2. Pre-energization cryogenic system step response test. Setpoint change from 72K to 68K

Fig. 2 shows a key performance experiment that was conducted prior to cable energization. The experiment began with the system operating stably at a baseline cable supply temperature of 72 K (±0.05) and a heat load requiring about 3 Kw of refrigeration. The subcooled LN2 supply temperature setpoint was then step changed to 68 K which initially required about 8 Kw of refrigeration. The substantial increase in refrigeration was a consequence of the several hour time delay before the return liquid begins to drop in temperature. During this transition period, the peak refrigeration demand was easily satisfied using the unique arrangement of the CRS which permits operation in a hybrid mode. During hybrid operation both the cryocooler and (back-up) bulk liquid nitrogen/vacuum blower system operate. After 6 hours of hybrid operation, the system returned to normal cryocooler operation.

Further experiments were conducted to verify stable back-up operation including:

- Cryocooler failure, vacuum/liquid nitrogen back-up. *0.6K momentary temperature rise before back-up.*
- Single liquid nitrogen pump failure. *15% momentary drop in flow rate.*
- Sensor failure: flow, pressure and temperature. *No effect due to alternative control strategies.*
- Site power failure. *Back-up generator provides sufficient power for control equipment and liquid nitrogen pumps. Cooling provided by bulk liquid nitrogen without vacuum blower. Temperature to cable will rise slowly, but remain subcooled.*

C. *Operation*

The overall cable system is monitored and controlled around the clock by the BOC Remote Operations Center (ROC) in Bethlehem, PA as shown in Fig. 3. The ROC is responsible for both operation of the CRS, and communication with the Eastern Regional Control Center (ERCC) of National Grid related to cable status and energization/de-energization. In addition to normal scheduled removal of the cable from service, there are procedures in place for emergency removal.

Fig. 3. Remote Operations Center. Albany HTS cable system is monitored from the BOC facility in Bethlehem, PA.

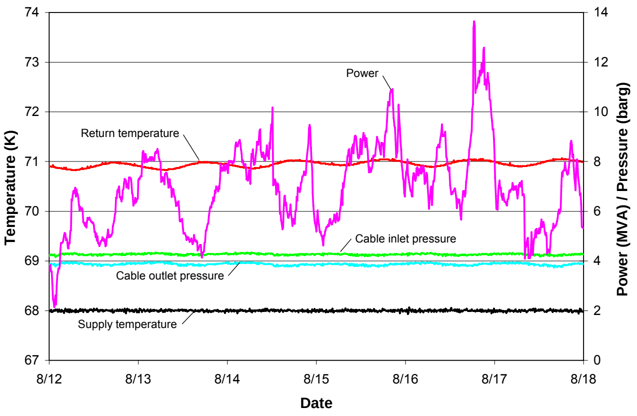

Fig. 4. Post-energization cable system operating conditions.

To supplement direct communication between the ROC and ERCC, there is dedicated control logic embedded in the onsite PLC. The dedicated critical alarm logic considers conditions which require immediate cable de-energization. The logic employs a data set structure which groups similar and redundant measurements (e.g., cable/coolant temperature, cable pressure, flow rate). There must typically be a vote of two independent measurements within a data set, and a prescribed time delay, to initiate a critical alarm. The critical alarm is then communicated directly to the ERCC via two independent hard wired signals.

The ROC has been monitoring and operating the HTS cable system continuously since before the end of cable cooldown on June 23, 2006. The cable was energized on July 20, 2006 and has operated continuously and stably from that time. Fig. 4 shows key operating parameters during a 1 week period in mid-August 2006.

III. INSTALLATION AND INITIAL COOLDOWN

After fabrication and successful completion of factory acceptance testing the HTS cable section, return cryostat, terminations and joint components were shipped from Osaka, Japan to Albany, NY. The cable and return pipe were pulled into existing underground ducts using conventional cable installation techniques. Measurements taken of the cables before and after installation indicated that no damage was incurred during the installation process.

The cable-to-cable joint fabrication was completed in the underground vault including fabrication and evacuation of the cryostat. The termination vessels were installed and connected to the HTS cable at each end. Vacuum jacketed piping connections were made between the CRS and the south termination vessel and return pipe, as well between the north termination and return cryostat. It is important to note that independent vacuum spaces are maintained for each flexible cryostat, the two termination vessels and for each field installed connection. All vacuum spaces can be monitored and maintained separately.

National Grid crews installed the necessary switches, surge arrestors, overhead conductor, and structures to connect the HTS cable to the existing 34.5 kV network. Current and voltage transformers were installed at one end of the HTS cable to monitor current and voltage on each phase of the cable. An ION 8600 meter was also installed to capture data in the event of any power quality issues such as a voltage fluctuation or fault current in the system.

Upon completion of the cable system installation an overpressure test of the entire system was conducted in accordance with ASME cryogenic piping codes (B31.3). The test was conducted using warm nitrogen gas. The pressure was raised in steps up to 110% of the installed pressure relief devices (PRD) designed to protect the system should liquid nitrogen flow be stopped thereby trapping cryogenic fluid in the cable. After the maximum pressure was reached it was held for 10 minutes and then the pressure was reduced to 100% of the PRD setting and held for several hours. During this time all field constructed joints were leak checked. No leaks were found and the cable system was ready to be cooled down.

The initial cooldown of the cable was completed without incident. A great deal of care was taken to ensure that no damage or leaks developed during the cooling process. Nitrogen gas was passed through the cable at various temperature and flow rates to maintain an even temperature gradient across the system. The final cooling was completed by filling the entire system with liquid nitrogen. When the system was filled liquid nitrogen began venting from the return line to the CRS as shown in Fig. 5. The temperature profile of the cable was continuously monitored by a fiber optic distributed temperature monitoring system developed by SEI. Thermal contraction and capacitance of the cable were also monitored throughout the cooldown process.

Fig. 5. Liquid nitrogen venting at end of the cooldown process.

The contraction of the cable measured by load cells installed at both termination vessels. The termination vessels are fixed at each end to that all of the contraction forces must be absorbed within the cable itself. The maximum tension measured during the cooldown was approximately 800kg. This is a relatively low value that is enabled by the ‘slack winding’ technique developed by SEI [7].

Results of the capacitance and tan delta measurements of the cable during the initial cooldown are shown in Fig. 5. As can be seen from the chart the capacitance of the cable decreased over time as the temperature of the cable decreased. When liquid nitrogen is introduced to the cable it begins to permeate the dielectric layers (PPLP) this will increase the dielectric constant of the cable. This is shown by the sharp rise in capacitance on the chart in Fig. 6. The cooling process of the cable is completed once the dielectric layers become fully saturated with liquid nitrogen and the capacitance of the cable becomes constant.

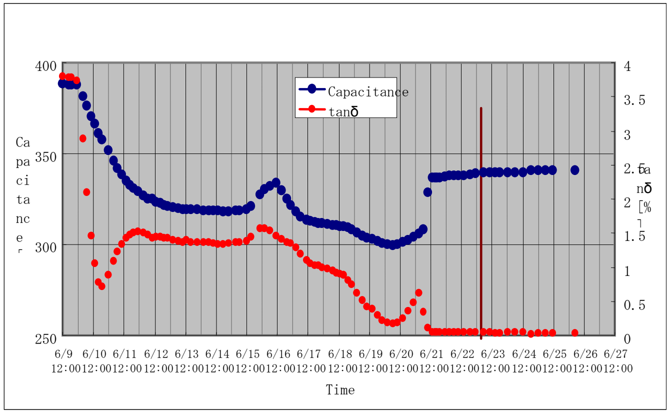

Fig. 6. Cable capacitance and tan delta during initial cooldown.

IV. PRE-COMMISSIONING TESTS

In order to ensure the HTS cable met all of its performance specifications and was ready to be operated on the grid a series of pre-commissioning, or pre-energization tests were performed. These test included confirmation of the heat in-leak through the cable cryostat, verification of the pressure drop across the cable, a DC critical current measurement, a DC withstand or hi-pot test, and finally a phase check between the HTS cable and the conventional overhead circuit.

Heat loss of cable was calculated by measuring the temperature rise across the cable at several flow rates. This requires very stable flow rates and temperature control over a period of days which the CRS handled easily. The measured values of heat loss were in good agreement with the design calculations. The total heat loss of the cable, excluding the terminations is approximately 1 kW with no electrical load applied. The total heat loss including the cable, joint, terminations, the return pipe and connection pipes is about 3.1 kW. This value does not include any losses associated with the CRS.

The pressure drop across the cable excluding the termination was measured to be 0.75 bar at 50 L/min. The elevation difference between the two ends of the cable is about 1 m and is accounted for in the calculation of the expected pressure drop of 0.7 bar.

Next the critical current of each cable conductor was measured using the 4 probe method and a DC current supply. Measured critical current for each of the three cable phases is about 2.3 kA at 73 K using the standard 1 μV/cm criterion. The temperature is the average between both cable ends at 40 L/min. The measured critical current corresponds with that measured prior to shipping the cable from Japan. Hence, the cable incurred no damage or degradation during the transportation, installation and initial cooling processes.

A DC withstand (or hi-pot) test was conducting according to the Association of Edison Illuminating Companies (AEIC C55-94) standard for 34.5 kV class underground cable. Voltage was applied to each phase of the cable in 10 kV increments up to 100 kV. The voltage was held constant for 5 minutes and then ramped down to zero. There were no indications of damage during this test.

Finally, a phase check between each phase of the HTS cable and the existing overhead line was conducted to ensure continuity from end to end. Upon completion of all pre-commissioning testing the cable was deemed ready to put into service on the grid.

On July 20th the HTS cable was put into service on National Grid's network. The cable was connected from the Riverside substation and voltage was applied for several hours. Upon completion of the voltage soak test the cable was connected at both ends and current began flowing through the HTS cable. There have been no interruptions since the cable has gone on-line and all parameters such as temperature, pressure and LN2 flow rate are being monitored and controlled by the BOC Remote Operations Center in Bethlehem, PA, without any on-site supervision.

V. LOAD FLOW STUDIES

The impact of a HTS Cable installed on an electric grid system was studied using the PSS/E power flow program [7]. Several load flow scenarios were studied to look at the impact of installing about 400m of HTS cable as well as if the entire line between the Riverside and Menands substations was replaced with a HTS cable. A parallel 115 kV line runs between the two substations. Load flows were also simulated with this 115 kV line taken out of service to see what the impact would be in a contingency situation.

A comparison of HTS cable to XLPE (conventional underground type) and overhead conductor is shown in Fig.7. Comparing the various types of cables shows that the HTS cable has a resistance approximately 300 times less than conventional XLPE cable and about 800 times less than overhead wire. The inductance of the cold dielectric HTS cable is 6 times less than conventional wire and 21 times less than overhead wire. The capacitance of the HTS is slightly less than conventional underground cable.

Cable Type	Resistance	Inductance	Capacitance
HTS Cold Dielectric	.0001 ohms/km	.06 mH/km	1.08 MVAR/km
XLPE Cable	.03 ohms/km	.36 mH/km	1.4 MVAR/km
Overhead Conductor	.08 ohms/km	1.26 mH/km	.05 MVAR/km

Fig. 7. Comparison of HTS, XLPE and Overhead cable properties

The existing conventional overhead line that existed prior to installing the HTS cable was used as the baseline for the load flow comparisons. Estimates of the MVA and MVAR loading in this configuration were made and compared to the other scenarios containing varying amounts of HTS cable. A summary of the various scenarios is summarized in Fig. 8.

When a portion of the line was replaced with an HTS cable the loading simulation increased, but only slightly. This is because the overall resistance of the line is only slightly lower than the regular line.

The next column in Fig. 8 represents a simulation done with the HTS cable comprising the entire distance from Substation #1 to Substation #2. This scenario does have an effect on the load flows. With this representation the flow is 5 times the watts and double the vars and causes a change in load flow path. The change in flow is not what you would expect if looking at the one line diagram from a purely mathematical perspective. The reason that the flow does not entirely go to the path of least resistance is the fact that each substation has a different phase angle. This phase angle difference will limit the current going in each path.

The final two columns in Fig. 8 represent the power flow analysis when the 115 kV line is taken out of service; first with the HTS cable forming 400 meters and the rest conventional wiring and secondly with the entire line comprising HTS cable from end to end. In the scenario where 400m of HTS cable is installed and the 115 kV is out of service the loading increased significantly to 9.6 MVA and 13.9 MVAR. The final scenario simulates the load flow that results when an HTS cable is installed between substations #1 and #2 and the 115 kV line is opened. This representation is the model that has the maximum load flow on Line #27; 13.7 MVA and 26.1 MVAR.

	Baseline (No HTS)	**400 m of HTS installed**	**All HTS from Sub #1 To Sub #2**	**400 m of HTS and 115kV line out**	**All HTS and 115 kV line out**
MVA	**.3**	**.4**	**3.4**	**9.6**	**13.7**
MVAR	**10.1**	**10.7**	**19.6**	**13.9**	**26.1**

Fig. 8. Table comparing relative load flow scenarios on the electric grid

VI. PRESENT LOADING CONDITIONS

The HTS cable is now in service on the 34.5kV National Grid 34.5 kV system. The following charts indicate the amount of flow and the cyclic natural of the load flow.

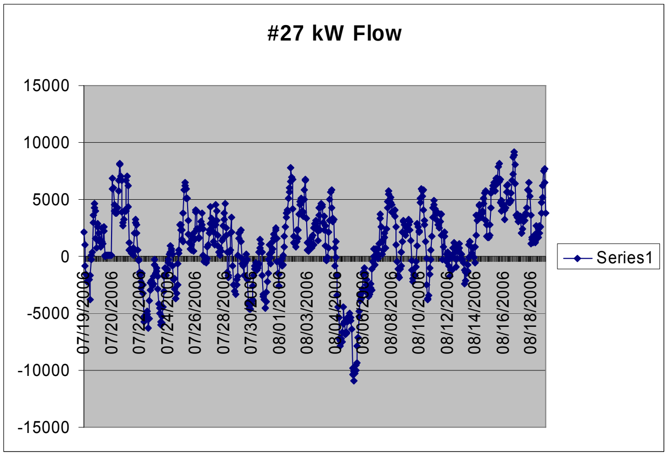

Fig. 9. Load flow in kW of Line #27 with HTS cable in service

Fig. 9 shows that the flow of energy can go in either direction through the HTS cable. To date there have been no issues associated with the HTS cable. National Grids ERCC reports that they have not treated this cable differently than any other cable or sub-transmission line in their system.

Observations from this HTS cable project yields many potential advantages from using this type of cable. Some of the advantages are as follows:

The higher current-carrying capacity of HTS cables will help a very congested underground area. A conduit that houses a cable carrying 200 amps will be able to be replaced with an HTS cable and now carry 1000 amps. This will relieve the over stressed part of a network system without having to dig and build a new duct bank. This will also have a reducing effect on the number of conductors on that portion of the network. Utilizing existing Rights-of-Way that are already in place if using the old duct banks will substantially decrease the costs for the permitting, construction and possibly environmental issues associated with a new installation.

Very low EMF due to the construction of the HTS cable is another benefit of this type cable. This benefits the utility by lower eddy current losses that would be generated on close metallic bodies; this also eliminates interference with telecommunications. This cable would lead to less cost for the system because of efficiency gains from the very small amount of losses due to heating. HTS cables will give greater control of the grid system with phase angles and FACTS devices.

VII. CONCLUSIONS

In order for HTS cable technology to be accepted by the electric utility community it is imperative to demonstrate that the technology is both reliable and to also evaluate the impact of operation in a real world utility application. Phase 1 of the ACP has been successfully installed, tested and energized on National Grid’s 34.5 kV network in Albany, NY. The cable system has been successfully operating since July 20, 2006 and is beginning to prove that the HTS cable and CRS utilized in the ACP is both reliable and effective. Simulation studies have shown that introducing 400m of a cold dielectric HTS cable on the 34.5 kV electric grid in Albany, NY has no adverse effects on the system.

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