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INSTALLATION AND COMMISSIONING OF TRIAX HTS CABLE

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ABSTRACT

A Tri-Axial high temperature superconducting cable system was installed by Southwire and nkt cables in the American Electric Power (AEP) grid in Columbus, OH in the United States. The cable is rated 13.2 kV and 3.0 kA for 69 MVA. The cable was installed underground with a cable-to-cable joint and serves as the connection between the step-down transformer and the distribution station bus. The cable was tested prior to being placed in service to verify performance parameters. The cable was placed in service on 8 August 2006 with load reaching 2,400 Amps (55 MW) on the first day of operation.

KEYWORDS

High temperature superconductor, superconducting, cryogenics, dielectric, cable, installation, underground.

INTRODUCTION

High temperature superconducting (HTS) cables have been under development around the world for many years. Superconductors offer the advantage of significantly higher power density and higher efficiencies as compared to conventional copper or aluminum cables. Current projects have addressed performance, reliability and economics of the technology in live utility grid demonstration projects. An innovative Triaxial cable design has been installed and placed in service at the Bixby Substation of American Electric Power in Columbus, Ohio USA. The cable operates at 13.2 kV with a continuous service rating of 3,000 Amps for 69 MVA. Design and testing of the cable and terminations has been discussed in detail by Sauers, et al [1].

The HTS cable connects a 84 MVA 138/13 kV transformer to the 13 kV distribution bus at the Bixby station. The cable provides 100% of the power to the 13 kV bus and all residential, commercial and light industrial customers served in the community around the station. Approximately 8,600 customers are connected to the station.

The Triaxial cable design places all three electrical phases concentric on a common cable core. The phases are made of BSCCO-2223 superconducting wires. A common copper concentric neutral is located outside the three phases. The cable design is shown in Figure 1. The HTS cable is placed inside a thermal envelope called a cryostat and the entire structure is flooded with liquid nitrogen (LN) to maintain an operating temperature of -202° C. Details of the cryogenic cooling system are outside the scope of this paper and have been discussed in detail by Lynch, et al [2].

The HTS cable is manufactured on a reel-to-reel process similar to conventional cables. The final cable was packaged on a 3 meter reel and shipped using standard methods from Cologne Germany to Columbus, OH in the United States.

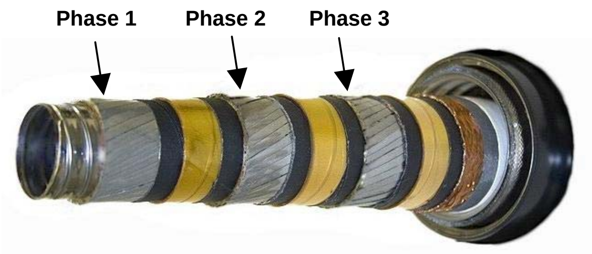

Figure 1: Triax superconducting cable.

Motivations for the Triax design include reduced material usage and reduced operating costs. The concentric phase arrangement allows for reduction by one half the quantity of HTS wires as compared to other cold dielectric HTS cable designs. The single core arrangements results in reduced AC losses and a smaller cold surface area – both factors to reduce cryogenic operating costs. These factors help bring the Triax cable to economic viability for certain applications.

INSTALLATION

General Layout

The cable circuit is 200 meters in length. Termination points are located at the North and South ends of the route. An underground vault for the cable joint is located approximately half way between the terminations. A joint was not required for 200 meter circuit, but was included to demonstrate field assembly and techniques for joining HTS cables.

A portion of the 200 meter cable was placed above ground in cable tray while the majority was pulled into an underground duct. The section was placed above ground to provide site visitors a visual reference for the cable. This section includes a 90 degree bend. The underground duct is located at a depth of approximately 2 meters and includes multiple 45 and 90 degree bends and is approximately 200 mm inside diameter.

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Cryostat Installation

The cryostat is made of two concentric, corrugated stainless steel tubes. Multiple layers of metalized mylar and spacers are located in the gap between the tubes. At the factory, a high level vacuum is achieved on the gap space to provide adequate thermal insulation for the HTS cable. After installation, the cryostat yielded heat leak of approximately 1.4 W/m into the system.

Two 100 meter sections of cryostat were delivered to the site on drums. The cryostat was manufactured with end fittings that provide secured ports to access the vacuum space to measure vacuum levels or pump on the vacuum space in the future, should this become necessary due to degradation.

The cryostat was pulled into the underground duct using standard pulling and rigging techniques. Rollers were placed adjacent to the duct entrance to ensure proper bend radii were maintained. A pulling-sock was used to attach the pull rope to the leading end of the cryostat. Standard cable pulling lubricants were used on the outside of the cryostat to reduce friction and pulling forces.

The first pull was from the north termination location into the underground vault with a maximum pulling force of 907 kg. The second pull was from the south termination location into the underground vault with a maximum pulling force of 907 kg. Inside the vault, a gap of approximately 3 meters was maintained between the ends of the cryostats to allow adequate space to assemble the cable joint.

HTS Cable Installation

The Triax HTS cable was pulled into the cryostat after the cryostat was in the ground as shown in figure 2. The delivered reel of HTS cable contained a single manufactured length of 220 meters. The reel was initially located at the south termination pad and the first cable pull was from this location into the underground vault with a maximum pulling force of 453 kg. After the pull, the cable was cut at the reel, leaving adequate slack for terminating.

Figure 2: HTS cable installation process.

The reel was relocated to the north termination pad and the remaining cable pulled from the north terminal into the underground vault with a maximum pulling force of 499 kg. Inside the vault, the two lengths of HTS cable were positioned with approximately 3 meters of overlap to allow sufficient cable to create a joint.

No conventional cable lubricants were used on the outside of the HTS cable prior to pulling into the cryostat. Such lubricants would have created contamination that would have caused damage to the cryogenic cooling system. Precautions were made to keep the surface of the HTS cable clean and prevent dirt or debris entry inside the cryostat.

Cable Joint

The two lengths of HTS cable were joined in the vault. The layers of HTS wires were joined together in such a manner to create low resistance connections. Semiconducting and dielectric layers in the cable were bridged between the cables to maintain proper voltage integrity. The completed cable-to-cable joint had a diameter only 5 mm larger than the manufactured cable.

A vacuum jacketed joint was created to connect both cryostat sections over the cable joint. Stainless steel tubes were field-welded over the cable joint. Metalized mylar layers are applied and a vacuum established between the layers of steel tube to create adequate thermal insulation at the joint. Figure 3 shows a picture of the completed cable joint.

Figure 3: Completed cable joint in vault.

Termination Assembly

Termination structures for the HTS cable facilitate the material transition from copper or aluminum to HTS wires. They also control the temperature gradients and transition from ambient temperature to -200° C while maintaining necessary dielectric strength. The termination structures for the Triax cable design include three phase bushings and a neutral connection. The outer enclosure is vacuum jacketed to provide adequate thermal insulation for the cryogenically cooled portion of the termination. External dielectric standoff is provided between the HV connection and grounded enclosure by means of an "off-the-shelf" outdoor bushing. Standard 4-hole NEMA pads provide connections to the conventional substation equipment.

The ends of the HTS cable are prepared to allow connections to the three concentric phases and concentric neutral. The vacuum jacketed enclosure is placed over the ends of the cable and the vertical components of each phase are assembled. The stainless steel enclosure is welded to the cryostat to create a thermally insulated joint between the two structures. Finally the liquid nitrogen flow connections are made to the end of the termination structure. The completed termination is shown in figure 4.

Each termination structure is instrumented to measure temperatures and pressures inside the enclosure. This information is relayed to the cryogenic control system and continuously monitored.

Figure 4: Triax HTS cable termination.

COOLDOWN AND TESTING

First Cool down

The cable system including joint and terminations was purged with dry nitrogen gas over several weeks as assembly was completed and liquid nitrogen piping connections were established. When the exit gas moisture content dropped to acceptable levels, the controlled cool down process was begun.

The nitrogen gas temperature was reduced in 25° C steps. Each step was maintained for a period of time as necessary to allow the exit temperature to stabilize at the reduced temperature. At approximately -175° C the limit was reached at which point the gas temperature could be reduced no further without introduction of liquid nitrogen into the cable. Liquid nitrogen at atmospheric pressure was flooded into the cable until liquid exited from the discharge at the end of the run. This entire process was completed in approximately 36 hours. See figure 5 for temperature trend during cool down.

The liquid nitrogen was bled through the system and discharged for several hours to clean and flush any contaminates from the system. After this time the cryogenic system was engaged, discharge valves were closed, and cryogenic pumps were employed to achieve the desired flow rate and pressure within the cable system. Sub cooling of the liquid nitrogen by the cryogenic cooling system results in a normal operating temperature of –203 °C.

Due to temperature decreases in the system, the HTS cable experiences thermal contractions that must be accommodated. Sufficient over-length of cable is established in the cable run to allow expected contractions without inducing harmful stress on connections and terminations. In addition, the termination enclosures were allowed to move slightly in response to contractions.

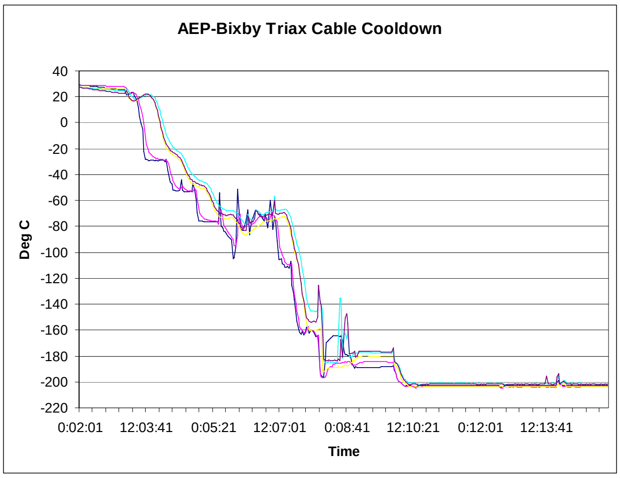

Figure 5: Temperature trend during cable cool down.

Off-line Electrical Testing

The cable system was allowed to fully stabilize at its normal operating temperature and pressure for a minimum of 24 hours prior to testing. This time ensures all layers of the HTS cable fully saturated with liquid nitrogen and all gas bubbles are collapsed or removed from the system.

High DC Currents

The HTS wires in the cable were tested to verify their superconducting properties after installation with up to 6,000 Amps direct current (dc) applied. Each phase of the cable was tested and the voltage rise along the length was measured. Results of the test indicated that no damage occurred to the HTS wires during installation.

VLF per IEEE 400.2

Electrical tests to verify dielectric integrity of all system components were conducted. Very Low Frequency (VLF) tests per IEEE 400.2 were performed on each phase. A voltage of 20 kV, 0.1 Hz for 30 minutes was applied between the phase conductors and between the outermost phase and concentric neutral. All phases passed the required tests.

Soak Test

A 24 hour soak test was performed by applying 13.2 kV line voltage to the cable. One end of the HTS cable was closed to the 13.2 kV distribution bus while open connections were maintained at the other end. The cable was maintained at line voltage for 24 hours. During this period charging currents were measured at the bushings of the HTS termination enclosures. These values, labeled phases A, B, C for the inner, middle and outer phases of the Triax cable

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respectively are shown in Figure 6. As expected due to the geometry of the Triax cable the three phases are not identical.

Warm Up to Ambient Temperature

During the testing described above a leak was discovered at a joint between two sections of vacuum jacketed piping used to return liquid nitrogen coolant from the cable to the cryogenic cooling system. The only method available to repair the leaking joint required warming the pipe, and thus the entire cable system back to ambient temperature.

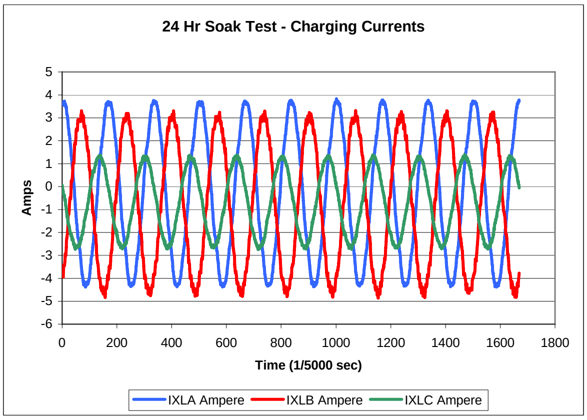

Figure 6: Measured charging currents during soak.

This unforeseen event allowed the opportunity to demonstrate operating procedures and processes to rapidly warm the system for repairs of a cable, cable joint or termination. The warm up process was conducted essentially in reverse of the cool down. The liquid nitrogen temperature was increased to the limit at which boiling occurred. At this stage the system pressure was reduced and cold nitrogen gas slightly warmer than liquid was introduced. The exit temperature was allowed to stabilize. The gas temperature was gradually increased in 25 degree steps to allow for a controlled warm up of the system. The entire warm up process took approximately 24 hours. During this time the movement of cable and terminations was monitored to document the effects of thermal expansion.

Second Cooldown

Repair of the leaking pipe joint was completed in approximately 2 days time. The cool down procedure described above was repeated for the second cable system cool down. Based on the previous experience and data, the system was returned to its normal operating temperature in approximately 24 hours. Again the movement of cable and terminations was monitored to note the effects of thermal contraction.

ENERGIZING HTS CABLE SYSTEM

On 8 August 2006 the HTS cable was placed in service. Utility company linemen and station operators followed pre-established switching procedures to initially place the HTS cable in parallel with the existing circuit, and ultimately remove the parallel circuit to place 100% of the station load on the HTS cable system.

The Bixby 13.2 kV distribution bus was previously operated with two parallel transformers feeding a split bus arrangement with a bus-tie breaker normally open. Installation of the HTS cable system included a third, paralleled transformer of a size capable to carry the entire station load. The standard operating parameters for the HTS cable include closure of the bus-tie breaker and disconnecting the previous transformers from the 13.2 kV distribution bus.

Switching steps to pick up load on the HTS cable were as follows:

1. Energize the dedicated 84 MVA transformer for HTS application
2. Close breaker to energize HTS cable with 13.2 kV line voltage.
3. Close load-side HTS breaker to place HTS cable in parallel with half of the 13.2 kV station load.
4. Open breaker to remove parallel transformer
5. Close bus-tie breaker
6. Open breaker to remove 2nd parallel transformer

Load curve for 8-August 2006 during the initial energization is shown in Figure 7. Peak load on the first day of cable operation was approximately 2,400 Amps. Normal daily load cycling has varied the load from 800 - 2400 Amps during the months of operation.

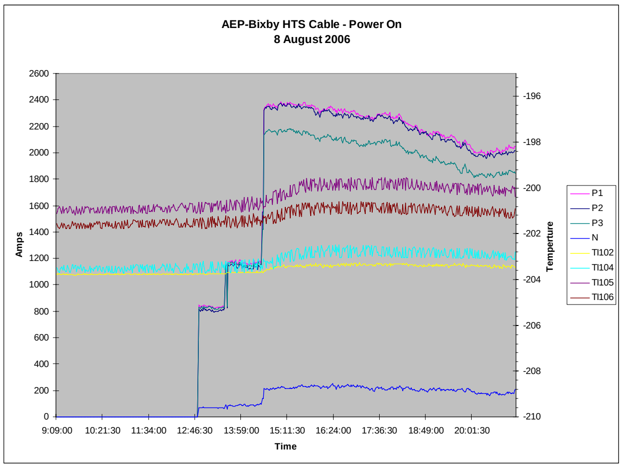

Figure 7: Day one load curve.

Unbalanced 3-phase loading of the seven distribution circuits leaving Bixby station created an unbalanced neutral current of approximately 200 Amps or 8% of the peak 2400 Amp load. This is well within the design parameters of the Triax HTS cable. Subsequent rebalancing of the seven load circuits drastically reduced this imbalance.

Temperature rise in the HTS cable system as a result of the addition of 55 MW of power was approximately 1 degree. This is attributed mainly to I^2R loss resulting from copper components in the terminations. These copper components are required to transition from normal to superconducting materials at cryogenic temperatures. The 1 degree temperature rise is well within design parameters.

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APPLICATIONS FOR DISTRIBUTION VOLTAGE HTS CABLES

The demonstration project at Bixby station has successfully shown the application of HTS cables to carry large amounts of power in a small, single cable. Distribution voltage superconducting cables are capable of replacing conventional high voltage transmission cable circuits and enabling the relocation of step down transformers from the load-end to source-end of the circuit.

The AEP project included 200 meters of cable between the transformer and distribution station bus. This distance can be extended up to several kilometers. Traditionally HV cables would be used to move power over this distance into a distribution station with local transformation. HTS cables allow transformer capacity at one location to be leveraged into a second station. This ability enables the utility to increase the utilization of existing transformer assets and avoid new transformer expenditures.

CONCLUSIONS

High temperature superconducting cable technology is making rapid advancements through developments by manufacturers worldwide. The development of the Triax cable design is a significant step towards commercially viable HTS cable projects due to its reduction in material usage and operating costs. The successful deployment of this technology at AEP has provided valuable lessons and information for future projects. The cable continues to operate and provide reliable service to the utility and its customers.

Acknowledgements

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GLOSSARY

HTS: High Temperature Superconductor