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NEW 345 KV UNDERGROUND EXTRUDED CABLE SYSTEM PROJECT IN CONNECTICUT

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ABSTRACT

The Connecticut Light & Power Company (CL&P, which is part of the Northeast Utilities System) energized a new 345-kilovolt (kV) electric transmission line in Connecticut in October, 2006. This project includes the first long-distance, 345-kV extruded cable installed in the United States. This paper describes the project route, the cable system employed, and unique aspects of the project, including a verification of the ampacity after installation, and use of a manhole cover restraint system for the unlikely event of an explosion in the vault.

As a result of this project, CL&P learned the importance of working closely with its Planning Department to provide accurate cable characteristics (e.g., capacitance, impedance) which are necessary and critical when a substantial amount of cable is installed on a power system with a source impedance that is relatively high compared to most power systems.

KEYWORDS

345 kV, solid dielectric, extruded dielectric, extra high voltage (EHV), tether, restraint system, ampacity verification, hybrid, siphon.

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INTRODUCTION

The Connecticut Light & Power Company (CL&P) energized a new 345-kilovolt (kV) electric transmission line between Bethel and Norwalk, Connecticut on October 12, 2006. This hybrid overhead/underground transmission line allows an additional 600 megawatts of electricity to be delivered to Southwest Connecticut and the region. This project was approved in the 2002 Regional Transmission Expansion Plan and is commonly referred to as the Bethel-to-Norwalk (B-N) Southwest Connecticut 345 kV Expansion Project.

This project is one of the world's largest 345-kV projects. It is also the first time that a long-distance, 345-kV extruded cable was installed in the United States. Most of the circuit route is comprised of overhead wire and traditional fluid-filled, pipe-type cable (also known as HPFF cable). However, for a 3.4-circuit kilometer segment of the cable system, the utility used extruded-dielectric technology.

The construction of this 345-kV connection is the first step towards enhancing the existing 345-kV grid comprising already 644 kilometers of overhead transmission lines. Other projects are currently in progress.

This paper focuses on the 3.4-circuit kilometer, extruded-dielectric cable portion of the B-N 345-kV Southwest Connecticut Expansion Project.

DESCRIPTION OF OVERALL PROJECT

History

Over the past several decades, electricity usage in Connecticut has increased significantly as a result of population increases, economic growth, and the expanded use of air conditioners and electronic devices such as computers. This growth in electricity usage is particularly evident in Southwest Connecticut, which encompasses 54 municipalities, including the metropolitan centers of New Haven, Waterbury, Danbury, Bridgeport, Norwalk, Stamford, and all of lower Fairfield County.

Southwest Connecticut was served by an electric transmission system of 115-kV lines and substations. It was the only major load pocket in New England that was not connected to the 345-kV backbone transmission system. Many of the lines in the region were installed more than 40 years ago and were never intended to support the present level of electric demand. Despite numerous upgrades and reinforcements that CL&P implemented over the last few decades, the 115-kV transmission system was no longer adequate to supply the area's continuing growth in electricity usage without extensive modification.

The urgency of this need has been highlighted by a series of recent events:

- In June 2000, the local area 115-kV system experienced a prolonged voltage depression following a contingency event that disconnected local customer loads. This event did not lead to cascading losses of transmission system elements or to a wide-area blackout, but it forewarned of this danger.

- o As reflected by the New England Independent System Operator (ISO-NE) issuance of “gap RFPs” (requests for proposal) for temporary emergency generation in Southwest Connecticut during the summers of 2002, 2003, and 2004, ISO-NE determined that Southwest Connecticut had inadequate transmission and generation resources.
- o On August 14, 2003, nine states and one Canadian province suffered a “blackout” originating from severe line and generator contingencies in Ohio. This blackout caused customer loads to be disconnected in Southwest Connecticut. Portions of the region were without power for more than 24 hours. If the 345-kV loop had been in place at the time of the blackout, the additional supply paths in Southwest Connecticut would likely have enabled a faster restoration.
- o During the five-year period preceding CL&P’s application for siting approval of the B-N 345-kV Southwest Connecticut Expansion Project, the peak load in the Norwalk-Stamford Sub-area increased by approximately 27%. The load growth in the Norwalk-Stamford Sub-area is driven by the commercial and 3 residential customer classes and consistently exceeds the overall load growth rate for the state of Connecticut.

Not only is this southwest area of Connecticut geographically isolated from the region’s 345-kV electric transmission grid, it also has limited generation. CL&P along with state and federal regulators have recognized this geographic isolation, and regional needs for reliable electric power supplies to support both existing and projected load growth. The B-N 345-kV Southwest Connecticut Expansion Project addresses part of this isolation, integrating southwestern Connecticut with the New England bulk power grid.

The B-N 345-kV Southwest Connecticut Expansion Project provides added capacity to serve the growing demands for electricity in the southwestern portion of the state, and will provide better opportunities for moving power to customers within the state for access to power from other Northeastern states. Specifically, the project will achieve the following:

- o Improve reliability by providing a new path for bulk power to flow into the area,
- o Increase capacity to a transmission-constrained area, responding to southwestern Connecticut’s demands for electric power,
- o Reduce existing transmission congestion and related costs which exceeded $300 million last year in the Connecticut sub-region of the New England Power Pool (NEPOOL), and which are expected to grow significantly in the next few years absent new power supply to the area,
- o Provide greater access to competitively priced generation, and
- o Accomplish these objectives by a means that strikes the appropriate balance between the lowest reasonable cost to consumers and the lowest reasonable environmental impact.

Planning and government evaluation of the line continued for years. The Regulatory Review began in July 2001 and the project was approved by the Siting Council in July 2003. Line construction began in Spring 2005 and was completed ahead of schedule.

Circuit Route

CL&P has an existing transmission corridor between the Plumtree Substation in Bethel and Norwalk Substation in Norwalk which is approximately 32 kilometers long and varies in width between 24 and 45 meters. An existing 115-kV transmission line occupies the entire length of the right-of-way between Plumtree and Norwalk substations; for 6 kilometers between Norwalk Junction and Norwalk Substation this circuit shares the right-of-way and support towers with one or more of two 115-kV circuits and a 27.6-kV circuit. Leaving the existing lines in place and constructing a new 345-kV line alongside was rejected over most of this route because too much additional right-of-way width – up to an additional 13-33 meters – was needed. Its cost and potential home acquisitions were strong considerations. To minimize the necessary right-of-way expansion, the project initially proposed removing a 115-kV circuit and rebuilding it on common steel poles with the new 345-kV line, each in a vertical configuration. This proposal would require much taller poles, and that was a cause for significant public objection during the siting process. Building underground lines over the entire route was not technically feasible or practical.

Numerous configurations of the new 345-kV and modified 115-kV lines were evaluated during an extensive state siting process. The final configuration approved by the Connecticut Siting Council is shown in Figure 1. This final configuration employs two separate segments of underground and two segments of overhead.

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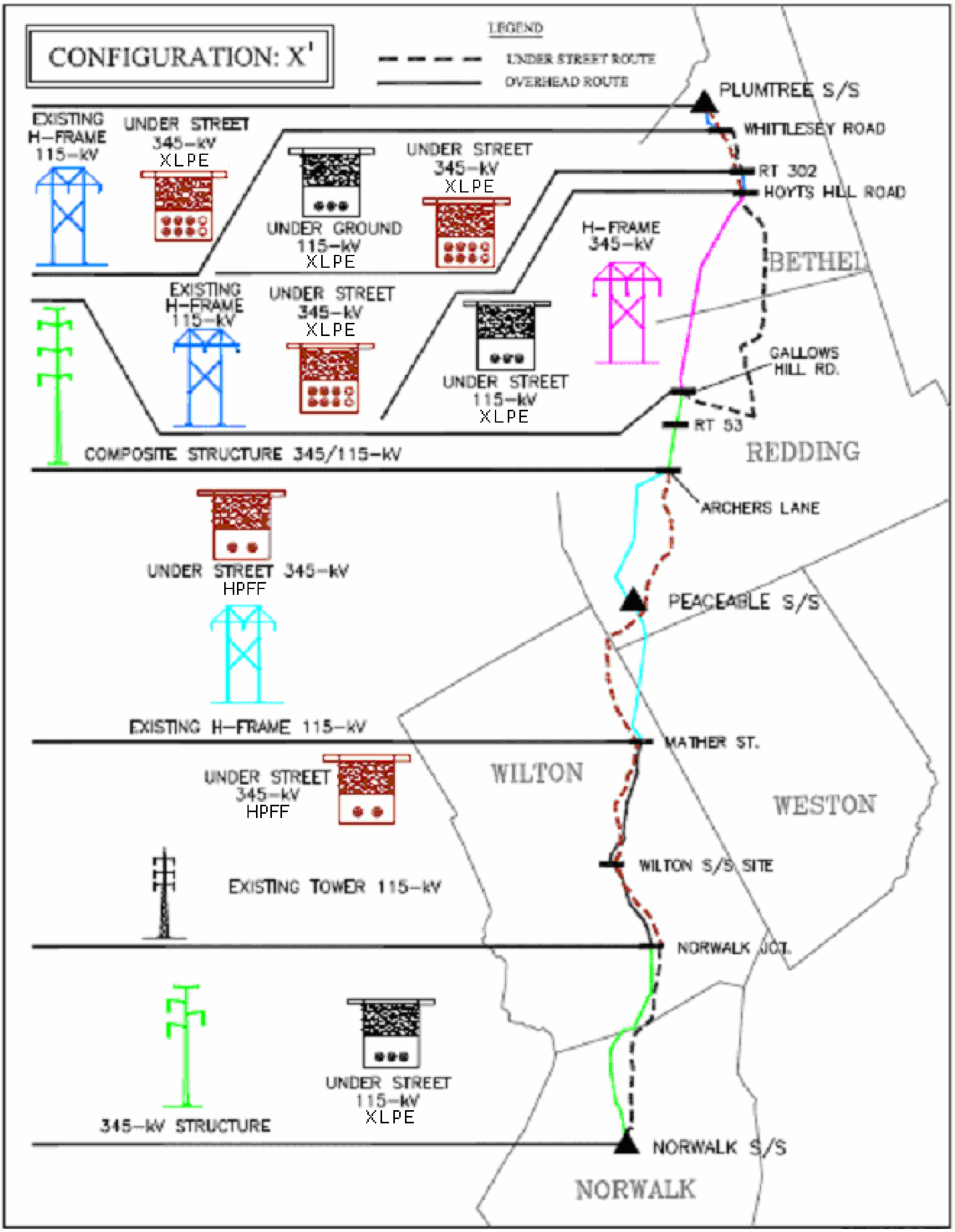

Figure 1: B-N 345-kV Southwest Connecticut Expansion Project final configuration

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Environment

The B-N 345-kV Southwest Connecticut Expansion Project proposals were evaluated with a strong emphasis on environmental concerns. The owner was proactive in obtaining a clear strategy from each of the bidders to show how the installation team proposed to manage and certify the work in a way that protected the environment. The use of geotechnical engineers and a professional environmental consultant was essential due to the differing environmental conditions along the route.

After contract award and prior to construction, composite soil samples were taken approximately every 150 meters along the route. Of the twenty-five samples taken, analytical data showed that seven samples exceeded Connecticut regulatory thresholds (typically the Residential Direct Exposure Criteria) for certain semi-volatile organic compounds. There were additional samples taken around these seven locations to define the parameters of the polluted areas. All soils deemed polluted were hauled to owner-approved facilities. Periodic monitoring took place for the duration of the project to ensure compliance with all regulations.

Water samples were collected from seven groundwater monitoring wells that were installed at locations determined by a professional environmental consultant. The purpose of this sampling was to characterize construction dewatering wastewater. Based on the analysis of groundwater, construction dewatering wastewater was determined suitable for discharge, in compliance with the project's Construction Stormwater General Permit and Stormwater Pollution Prevention Plan.

There were several key areas of environmental concern during construction. The areas outside the Plumtree Substation and the Hoyts Hill Transition Station offered challenges to the duct bank construction as well as the installation methods to be employed because of wet conditions. The project had to consider the structural integrity of the duct system as well as transversing the terrain so as not to alter existing environmental conditions. The site of a jack and bore across the East Swamp Brook presented unique challenges for construction due to the porous rock streambed. A 48-inch (1220-mm) reinforced concrete pipe was jacked in 1.5 meters below the streambed while controlling water infiltration. The project utilized professional Environmental Consultants to design remediation plans, as well as onsite project Environmental Coordinators to monitor daily activities.

The 3.4-kilometer segment of the B-N 345-kV Southwest Connecticut Expansion Project was executed utilizing environmentally sound principles through the work of a dedicated owner and an environmentally focused team.

DESCRIPTION OF CABLE SYSTEM

The line had two cables per phase, installed in a 4 by 2 concrete-encased duct bank. The ducts were nominal 6-inch (150-mm) diameter which was considered adequate for the1750 kcmil (887-mm^2) conductor cable (CL&P is using nominal 8-inch (200-mm) ducts on a related 39-kilometer line which is using 3000-kcmil (1520-mm^2) conductor cable). Figure 2 shows the typical trench cross-section.

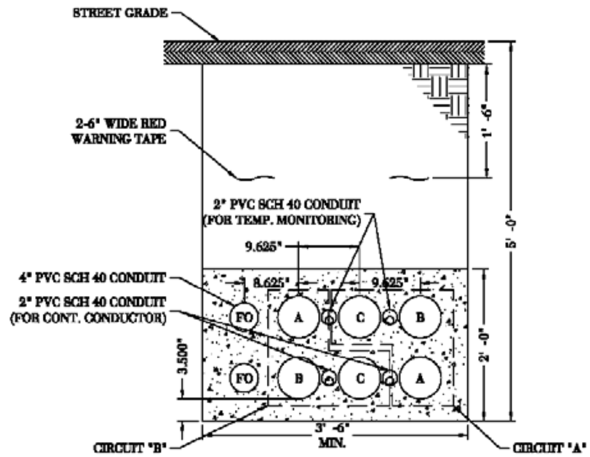

Figure 2: Trench cross-section

Technical Issues

Tethered Manhole Cover Restraints

At the same time as this project, CL&P was also designing another large, 345-kV, XLPE-insulated cable projects to be built predominately along 39 kilometers of heavily traveled state roads in Southwest Connecticut. As part of that and other projects, CL&P designed a vault that would minimize traffic disruption during installation while maintaining a safe working environment for maintenance crews during work periods inside the vault. Along with the vault development, CL&P also designed a dual-chamber vault that provides safety for workers on one side of a double concrete wall in event of a failure and explosion on the other side, along with a tether restraint system to secure the vault covers in the unlikely event of a vault explosion [1]. The tether restraint system was to be employed in an Educational Park on this portion of the B-N 345-kV Southwest Connecticut Expansion Project.

To design the tether restraint system (in addition to the newly designed vault for the other projects), CL&P worked with consultants to determine the maximum pressure the vault and tether restraint system would be exposed to in the event of an explosion. A hypothetical worst case short circuit with average RMS arc voltage of 1.5 kV, RMS current of 63 kA, and duration 18 cycles - plus an explosion consisting of the vault filled with 10 percent methane (which has more explosive energy than the combustion of byproducts from the arc) would conservatively produce a peak pressure rise inside the test vault of about 16 psi over a short duration of 300 milliseconds. Adding a safety factor of three, this translated to 300,000 pounds (1,300,000 Newtons) force on the cover.

The predicted pressures showed that trying to hold the manhole cover down so that it could not move was not a feasible solution. It is far better to let the cover move upward a limited distance so the high-pressure gases can vent while maintaining the internal pressure at lower levels.

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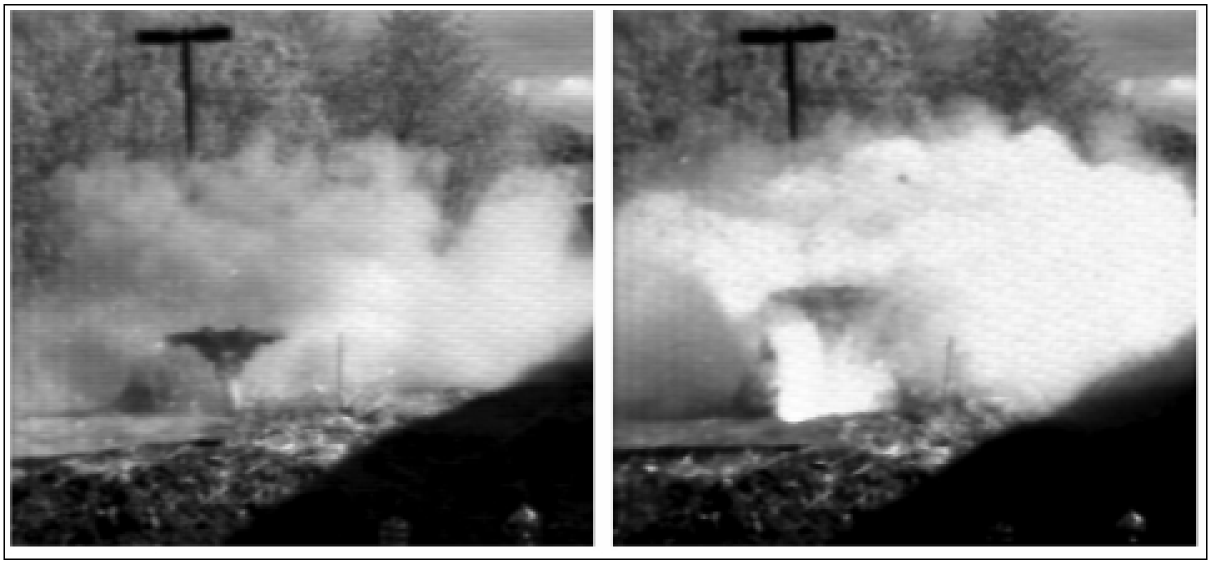

Figure 3: Pictures showing the tether as it restrains the manhole cover during vault explosion testing

The manhole cover was thus tethered by a short length of very high strength elastic webbing much like traditional seat belt material. The tether was threaded through a metal loop cast into the concrete floor of the vault, with another loop attached to the cast iron manhole cover.

For the actual test of the tether restraint system as well as the pressure-withstand of the vault itself, a full-size 9-meter long vault was installed outdoors at the test laboratory and a high-energy arcing fault was introduced by applying a voltage of 16 kV single-phase at a frequency of 60 Hz, with a 63 kA RMS symmetrical current for 18 cycles to an intentionally faulted splice for the first test, then cable for the second test, each creating an explosion. The same tether restraint system was thus tested twice, restraining the manhole covers both times. See Figure 3.

System Integration

CL&P, as with all companies, performs detailed studies to ensure the stability and reliability of the transmission system whenever changes are proposed such as the addition of new transmission lines. These studies are based on very specific assumptions for system parameters and characteristics. For an underground system, these parameters and characteristics are affected to some degree by actual field conditions and actual cable installed. However, these studies are run prior to installation, even prior to cable award or detailed engineering.

Early system planning studies for the B-N 345-kV Southwest Connecticut Expansion Project showed that temporary overvoltages caused by harmonic resonance was a primary area of concern. This propensity for harmonic resonance was due to the relatively high system impedance in series with the capacitance of the underground cable segments [2] [3]. Since CL&P's transmission system in southwest Connecticut has such high system impedance compared to most power systems, small changes to the cable system characteristics can change the outcome of the system planning studies. This contrasts with most transmission cable installations, where the system is strong enough that inevitable changes in characteristics for the as-built cable do not affect system operation.

For a power system with a high source impedance such as CL&P's southwest Connecticut system, if any changes occur to the cable system characteristics from those which were originally studied, then multiple studies (which are expensive and time consuming) by the Planning and Protection & Controls departments may be required to determine that the new characteristics do not adversely affect system operation. Potential changes to the system that might affect system characteristics include changes to the cable sheath bonding arrangement, duct bank parameters including spacing between vaults, cable phase location, cable insulation material or thickness including manufacturer's tolerances and values of intrinsic insulation parameters, cable sheath material or thickness, conductor material or size, ground resistivity, and ground continuity conductor size or location.

On the B-N 345-kV Expansion Project, CL&P learned the following valuable lessons, which will be applied to future projects:

- o Cable impedance and susceptance are very important to the Planning and Protection & Controls departments. Planning uses the data in steady-state (thermal & voltage), transient stability, temporary overvoltage (TOV), transient recovery voltage (TRV), and pre-insertion resistor studies. Protection & Controls requires the data for use in short-circuit analysis as well as protective system design and analysis.

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- Manufacturers do not calculate impedances as precisely as CL&P requires for these studies. Also, there is some variation amongst manufacturers in how they calculate impedances. These are very complex calculations. Therefore, do not rely on the manufacturers or even architect engineering firms for calculations of impedance; retain the services of an outside expert.
- Provide the Planning and Protection & Controls departments with a realistic worst-case range of system characteristics and parameters so that when changes occur during detailed design, cable fabrication, and construction, new studies won't be required. In addition, base the characteristics and parameters as much as possible on detailed design and real-world data, including actual field measurements. Be sure that the study results allow for a range of characteristics and parameters, to allow the designers and installers to accommodate the inevitable changes that occur during detailed design and installation.
- Build a system as near to the preliminary design as possible by incorporating the same characteristics and parameters used in the system studies as requirements in the civil and electrical bid documents. When changes are required due to field conditions or changes in system requirements, ensure that the changes do not result in cable characteristics that are beyond the range of parameters assumed during initial studies.
- Make the impedance calculations a specific task in the cable system planning, protection and control, and design studies, with circulation and sign-off from all affected departments.
- Maintain a constant flow of communication between the Engineering, Planning, and Protection & Controls departments, and obtain input from cable manufacturers and the impedance calculation expert as soon as possible.
- Perform as-built series impedance measurements to verify the calculations when the studies show that variations could be a serious detriment to the system performance.

Variable shunt reactors were installed to compensate up to 97% of the reactive volt-amperes caused by the cable shunt capacitance.

Cable Core

The 345-kV cable supplied for the project complies with ICEA S-108-720-2004 [4] and some applicable requirements of AEIC CS7-93 [5].

The cable structure is presented in Figure 4.

The specified ampacity requirements (1084 amperes/line during normal operation and 1329 amperes/line during 12-hour emergency at 813 amperes preload) are achieved with a 1750-kcmil (887-mm²) copper segmented conductor.

The cable insulation is dry extruded XLPE. The insulation thickness of the cable (26 mm – 1023 mils) has been chosen based on experience obtained in several long-term tests on complete cable systems including significant lengths of cable, splices and terminations carried out according to various CIGRE recommendations [6][7].

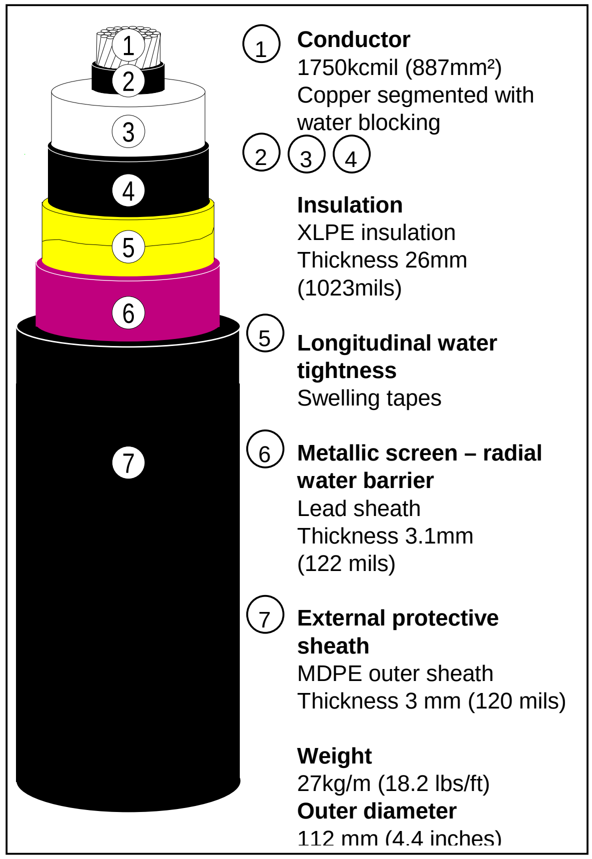

Figure 4: 345-kV cable structure

Resulting operating stresses are 12.5 kV/mm on the conductor screen and 5.5 kV/mm at the screen over the insulation [8].

Short-circuit current carrying capability (50 kA; 14 cycles) as well as radial water barrier is obtained using a lead sheath of a minimum of 3.1 mm (122 mils) thick. Longitudinal water blocking is achieved by swelling tapes in the conductor and below the lead sheath.

The MDPE outer sheath is 3 mm (120 mils) thick.

Cable Accessories

Splices are of the "one-piece premoulded" type as described in Technical Brochures 89 [9] and 177 [10] issued by CIGRE WG 21.06. They are equipped with a copper casing plumbed onto the cable lead sheath.

The terminations are SF6-filled and housed in porcelain insulators. The link or cross-bonding boxes installed in the vaults are equipped with transparent covers to allow for a visual maintenance inspection using a flexible fiber optic camera.

Tests on Cable System Components

Type tests on complete components of the cable system as well as non-electrical tests on individual components including specific tests related to water tightness properties were performed. The test sequences are reported hereafter.

Electrical type tests on the cable system components

The test loop for the electrical type tests (Figure 5) was composed of the following:

- Two outdoor terminations filled with SF6 and equipped with porcelain insulators,
- 18 m of lead sheathed cable,
- One "one-piece premoulded splice" with shield interruption.

The test sequence was as per IEC 62067 [11] section 12.4 requirements:

- Bending test,
- Measurement of partial discharges at 285 kV at ambient temperature,
- Measurement of tan delta of loss angle at 95 to 100°C at 190 kV,
- Heating cycle voltage test (20 cycles at 380 kV – conductor temperature between 95 and 100°C),
- Switching impulse test at 950 kV; conductor temperature between 95 and 100°C,
- Lightning impulse test at 1300 kV, conductor temperature between 95 and 100°C,
- Withstand test at power frequency 15 min at 380 kV,
- Measurement of partial discharges at ambient temperature and at 95 to 100°C at 190 kV, and
- Measurement of the tan delta of the loss angle at 95 to 100°C at 190 kV.

All results complied with IEC 62067 requirements, including the non-electrical type test sequences.

Figure 5: Type test cable loop during withstand test at power frequency

Water penetration test on the premolded splice

Once the electrical type tests were completed, the premolded joint with shield interruption was taken off from the cable loop and then submitted to the water tightness test described in Annex D of IEC 62067.

The premolded joint was immersed in a tank under a pressure equivalent to 1 m of immersion depth (Figure 6) and the following sequences and tests were performed:

- 20 heating /cooling cycles with a water temperature comprised between 70 and 75°C.
- After this cycling and with the joint still immersed, a DC test is performed on the outer protection (1 min at 20 kV) and an impulse voltage test as well (10 positive and 10 negative impulses at 62.5 kV).
- This sequence was followed by the tests of the shield interruption including a DC test (1 min at 20 kV) and an impulse voltage test (10 positive and 10 negative impulses at 125 kV).

All tests performed fulfilled the standard requirements.

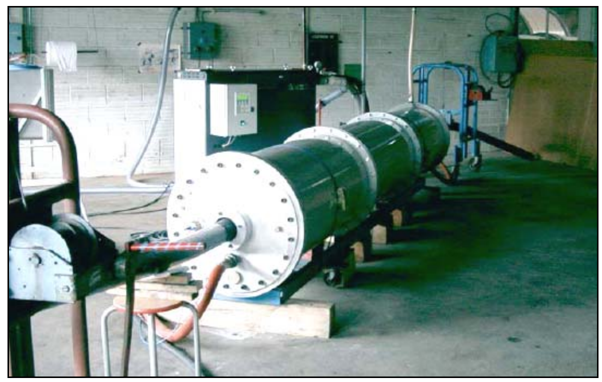

Figure 6: Water penetration test of a premolded joint

Structural stability test followed by a water penetration test on the cable

The water penetration test was performed according to IEC 62067 annex C. The sample used for this test was first submitted to the structural stability test described in AEIC CS7-93 section D3.

This structural stability test corresponds to the following sequences:

- Measurement of partial discharge at 200, 300, 400 and 500 kV at ambient temperature, after 6 hours at 90°C, after 6 hours at 105°C, and once again at ambient temperature,
- Measurement of dissipation factor at 200 kV at ambient temperature, after 6 hours at 90°C, after 6 hours at 105°C, and once again at ambient temperature.

Eight meters of previously tested cable were used to measure the water penetration in the conductor and under the water barrier. After 24 hours at ambient temperature, the samples were subjected to 10 heating cycles at 95°C on the conductor and opened. No water penetration over 2.9m was observed (to be compared to the 4m on each side of the water injection as specified in the IEC 62067 standard).

Installation Methods

The laying of the cables started in May 2006. The installation of joints was made in the vaults under a splice trailer (Figure 7) which was located above the manhole. The trailer provided the splicers with an electric supply for lighting, heating, and all appropriate handling equipment. The trailer is also equipped with air conditioning. When the splicing was completed, the trailer would be moved to the next vault. See Figure 8.

The cable system was completed in September 2006.

Figure. 7: Outer and inner views of the trailer with the integrated access to the manhole

Figure 8: Preparation of splices in manhole

After-Laying Tests

The following field-acceptance tests were required after the cable installation was completed:

- o A jacket integrity test (10kV dc for 1 minute).
- o An AC voltage withstand test in accordance with IEC 62067 Section 14.2.
- o A 72-hour soak test at rated ac voltage and with the XLPE cable segment carrying load.
- o Partial discharge measurement on the full cable system at rated voltage. A measurement at 250 kV was also performed. See Figure 9.

As-built ampacity verification

In addition to the above-mentioned tests, CL&P also required an as-built ampacity verification be performed based on the hottest time of the year. As such, the contractor was required to deliver a cable system that could deliver a certain, guaranteed ampacity year round.
However, the verification process was challenging, because it needed to be completed within a relatively short period of time after cable installation. Even though CL&P installed an optical fiber in a duct adjacent to the cable for measuring temperature, the cable would need to operate at about 50% of its designed ampacity for several months before sufficient temperature rise above its surroundings could be measured, and CL&P was not certain that the cables would have the required loading. Therefore, a unique test was developed, which is described in the following paragraphs.

The first step towards verifying the ampacity of the new line was to measure of the earth ambient temperature along the route of the newly installed cable shortly after the distributed temperature sensing (DTS) optical fiber was completed end-to-end but no sooner than fourteen days after the final pour of concrete for the duct bank. At the same time, numerous thermocouple probes that were installed along the route were also read as a correlation to the DTS fiber readings and vice versa.

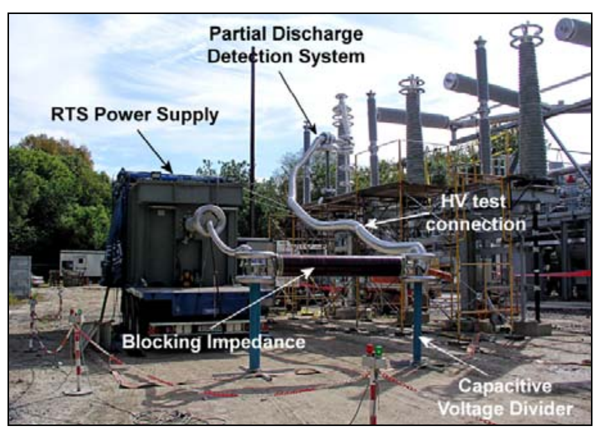

Figure 9: AC Highpot test and PD measurement test set-up

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The next step was to reconcile the earth ambient temperature readings with the as-built drawings. In order to predict the expected temperature at the various depths for a given time of year, calculations were performed based on the difference between the maximum mean and annual mean air temperature for the cable location, and the thermal diffusivity of the specific soil type at site [12]. With this data, the soil temperature at different depths and times was calculated. Where the DTS optical fiber temperature measurements exceeded the predicted temperature, the temperature difference was noted, the cause determined when possible, and the increment applied to the design ambient earth temperature during the ampacity calculation.

After all potential hot spots were identified the as-built ampacity verification ensued. The contractor calculated the expected cable conductor temperature at each hot spot location at the guaranteed minimum ampere rating based on the expected ambient earth temperatures at the hottest time of the year. The calculation parameters for earth and concrete duct bank envelope thermal resistivity were based on actual measurements taken throughout the installation and adjusted based on 3% moisture content based upon dryout curves developed by a soil thermal specialist.

As an example, the September 1 temperature at 8 feet (2.4 meters) is expected to be 18°C. A DTS optical fiber temperature measurement is taken on April 1 and shows a temperature of 6°C at 8 feet (2.4 meters). Based on the calculation described earlier, the expected temperature at an 8-foot (2.4-meter) depth on April 1 is actually 2°C. Since the difference between 6°C and 2°C is 4°C (the hot spot temperature elevation), the contractor uses 18°C plus 4°C (or 22°C) as the ambient earth temperature for ampacity verification for that cable location at 8 feet (2.4 meters) and during the hottest time of the year (i.e., September 1).

CONCLUSION

CL&P designed and installed the first 345-kV XLPE-insulated cable system with splices in the United States. The cable system was one segment of a hybrid overhead/underground transmission line. Installation was in a duct-and-vault system that is preferred in congested U.S. city streets. A special manhole cover restraint system using tethers was designed and tested to demonstrate safety in event of an electrical failure and explosion in the vault. Environmental concerns were paramount in the design and installation. Cable electrical characteristics were very important to allow the cables to operate satisfactorily in the relatively weak electrical system in southwest Connecticut. Extensive field testing verified the electrical and thermal performance of the cable system.

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GLOSSARY

B-N: The portion of the Connecticut Light & Power Company’s transmission cable project from Bethel, Connecticut to Norwalk, Connecticut
CL&P: Connecticut Light & Power Company
DTS: Distributed Temperature Sensing
EHV: Extra High Voltage
HPFF: High-Pressure, Fluid-Filled cable, also called pipe-type cable
ISO-NE: New England Independent System Operator
kV: kilovolt
NEPOOL: New England Power Pool
RFP: Request for Proposal
ROW: Right-of-Way
TOV: Temporary Overvoltage
TRV: Transient Recovery Voltage
XLPE: Cross-Linked Polyethylene