Underground Power Cable Considerations: Alternatives to Overhead

Presented at
47th Minnesota Power Systems Conference (MIPSYCON)
1-3 November 2011
Earle Brown Heritage Center
6155 Earle Brown Drive
Brooklyn Center, Minnesota

Earle C. (Rusty) Bascom, III
Victor D. Antoniello
ELECTRICAL CONSULTING ENGINEERS, P.C.
Schenectady, New York

Abstract — *Underground cables are a viable alternative to overhead transmission lines when proper consideration is given to the many details of using these types of systems. Cables, however, have differing characteristics than overhead lines that must be factored into design, ratings, switching, reactive compensation, operation, maintenance and repair. This paper provides an introduction to the cable system types and presents an overview into considerations for using underground cable systems. The discussion is focused on transmission cables but also has relevance for distribution cable applications.*

I. INTRODUCTION

Increasingly, utilities, developers and power producers seeking to build new power transmission systems are required to at least consider underground cables as an alternative to overhead lines. This may be from the standpoint of due diligence when requesting regulatory approval for an overhead line or as part of a hybrid line where a portion of an otherwise overhead circuit must be built underground either for reasons of congestion near substations or other restrictions that would otherwise prevent construction of an overhead circuit (proximity to schools or hospitals, constraints on available rights-of-way, concerns about magnetic and electric fields, etc.).

In deciding to use underground cable systems, there are many technical issues to consider. The paper summarizes the many details that should be considered, and the reference section is intended to provide the reader with additional background that may be helpful in gaining further understanding on the various topics.

II. CABLE COMPONENTS AND SYSTEM TYPES

A. Basic Cable Components

Insulated power cables have two basic components; a conductor to carry current and insulation to support the line-to-ground voltage. Conductors are made of stranded copper or aluminum; sometimes larger conductors are arranged in segments to reduce losses. Current-carrying capacity increases with conductor size.

The predominate insulation materials are laminar taped paper or laminated paper polypropylene (LPP) for dielectric oil-filled cables, or extruded cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR) for extruded cables. Increased insulation thickness will support higher line-to-ground voltage, although voltage class is designated based on rated line-to-line system voltage. Limiting moisture ingress for all cable types is important; EPR-insulated cable and XLPE distribution cable with tree-retardant additives have been found to be more tolerant to the effects of moisture and do not require a radial moisture barrier (metallic sheath).

Conductor and insulation shields on, respectively, the inside and outside of the insulation help control electrical stress. Other components of each cable type are described below.

B. Extruded Dielectric Cable Type

Extruded cables are so called because the insulation material (XLPE or EPR) is shaped by passing heated polymers, which are vulcanized, through a die to provide the required insulation thickness over the conductor. A metallic shield, if present, of tape or, wire of copper or aluminum may be applied over the insulation. A radial moisture barrier (e.g., metallic sheath), if present, may consist of extruded lead, corrugated or foil made of copper or aluminum, or corrugated stainless steel. The metallic shield and sheath carry charging current and fault current. An insulating jacket over the shield or sheath provides electrical isolation of the shield/sheath from local ground and mechanical and corrosion protection to the cable. Three-conductor cables are available up to 138kV, but the vast majority of underground extruded circuits use single-conductor cables. Transmission cables are often 3-5in (75-125mm) in diameter and may be installed directly buried or in, typically, 6-8in (152-203mm) plastic conduits with commercial installations up to 500kV. Most extruded cables are ac, but a very few are dc.

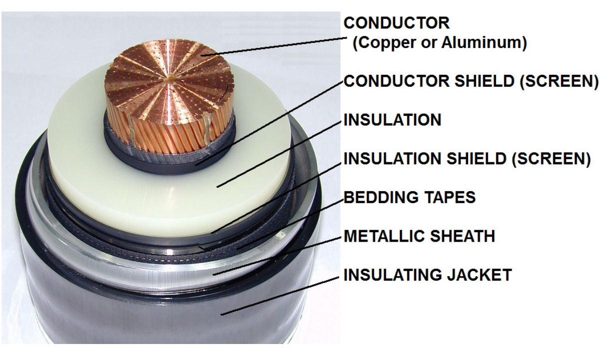

Figure 1: Components of an extruded cable.

C. Pipe-Type Cable

High-pressure pipe-type (HPPT) cables are so designated because of the carbon steel line pipe used to contain the cables and filling medium under high pressure, which is an integral part of this system type; most new installations use nominal 8in (219mm) pipes with ¼-in (6.35mm) wall, but 5in, 6in, 10in and 12in (141mm, 168mm, 273mm, 324mm) pipes have been used. Paper or LPP insulation is helically taped over the conductor shield to the required thickness, vacuum dried and impregnated with dielectric oil. A metallic skid wire over the high-resistance shield provides mechanical protection while the cables are pulled into the pre-installed pipe and from movement during load cycling. HPPT cables are typically 2-3.5in (50-90mm) in diameter, and all three phases are installed simultaneously in the carbon steel line pipe.

The steel pipe is protected from the surrounding environment and corrosion by an insulated coating of polyethylene tape, fusion bonded epoxy and polymer concrete, or asphalt mastic. A cathodic protection system is important to further protect the pipe from corrosion. For voltages up to 138kV, the pipe can be filled with dry nitrogen gas (high-pressure gas-filled, HPGF), though synthetic dielectric oils (alkylbenze or polybutene) are used for all voltages up to 345kV (high-pressure fluid-filled, HPFF, or oil-filled, HPOF); either system is nominally pressurized to 200psig (1.4MPa).

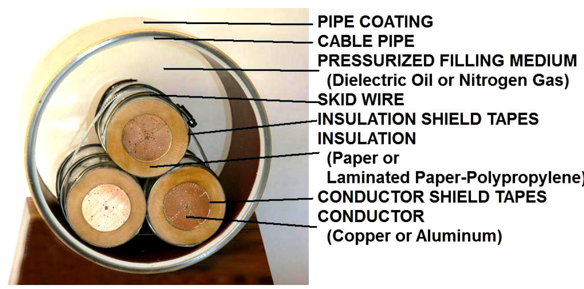

Figure 2: Components of a pipe-type cable.

D. Self-Contained Fluid Filled Cable Type

Self-contained fluid-filled (SCFF) cables use laminar paper or LPP insulation. A fluid channel in the middle of the conductor (or in the interstices between cores of three-conductor cables) permits dielectric oil expansion and contraction under pressure, inhibiting insulation voids from forming. A moisture-impervious metallic sheath, similar to an extruded cable, contains a positive internal pressure (15-75psig, 0.1-0.5MPa), and an insulating jacket is put over the sheath. These cables can be manufactured in very long splice-free lengths which make them useful for submarine projects, though use is diminishing worldwide. As with extruded cables, armor wires may be applied over the jacket if designed for submarine projects; most installations are direct buried.

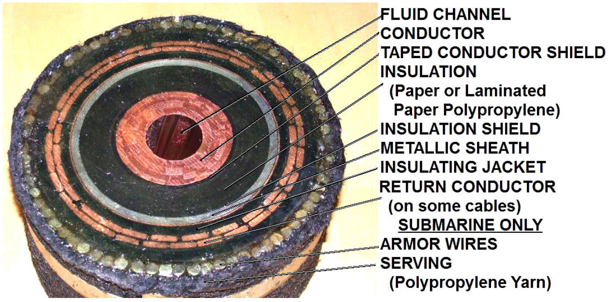

Figure 3: Components of a self-contained cable.

E. Other Cable Types

Mass-impregnated cables are somewhat similar to SCFF cables and are used exclusively for long DC submarine cable installations. Compressed gas-insulated transmission lines have very high current-carrying capacity and are generally limited to very short above ground runs (~1000ft, 300m) within substations due to their high costs, susceptibility to corrosion and large space requirements. Superconducting cables have seen very limited commercial applications, mainly due to the high system costs and ongoing development of cryogenic systems.

F. Accessories

Aside from the cable, joints for connecting adjacent cable sections and terminations for connecting cables to other equipment, along with other accessories, are needed to complete the cable system. Link boxes with grounding links, sheath voltage limiters and features to permit cross bonding, plus associated bonding cables and ground continuity conductors, are needed for extruded cable systems. Shipping container-sized dielectric oil pressurization plants (HPGF systems uses a much smaller, nitrogen gas cabinet) and cathodic protection systems are needed for HPPT cables, and fluid reservoirs are needed for SCFF cables. Vaults (e.g., "manholes") typically, 8ft wide (2.4m) x 7ft (2m) tall x 16-33ft (5-10m) long, depending on voltage and system type, are used for most joints in North America, although direct buried joints are possible and common in other parts of the world. Near terminals, HPPT cables require special trifurcators to separate the three cable phases in the steel line pipe into three separate stainless steel pipes.

III. SYSTEM PLANNING CONSIDERATIONS

A. Route Selection & Rights-of-Way

Cable systems are most often used where rights-of-way are limited, typically in urban settings. Routing through streets is common because the utility corridor is already established and structures above cable lines are not possible for fear of damaging the cables or limiting access for repairs. Available space for installation may still be constrained by other underground ground utilities.

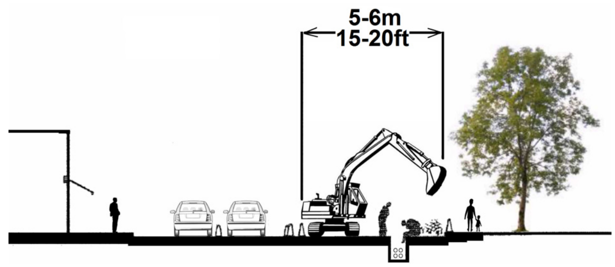

Figure 4: Example cable right of way in a city street.

The permanent right of way may be a few feet (~1m) across, but temporary easements are needed for construction and to access splice vaults for maintenance. Routing should consider stakeholder impact, future construction plans along the line and accessibility.

B. Types of Terminal Stations

There are essentially two ways to terminate underground cable circuits; substations and transition poles. Substations require more space and usually a fenced perimeter, but they allow greater flexibility for connecting other equipment and can more easily support multiple cables per phase or installed spare conductors. HPPT usually require some type of substation, at least at one end, to house the pressurization and cathodic protection equipment.

Compact transition poles are convenient for areas where siting a new substation is not practical and, in particular, for "hybrid" lines where there are intermediate underground dips in an otherwise overhead line.

C. Power System Considerations

Cables are essentially long distributed capacitors that generate capacitive vars. Significant charging current generated in AC cable systems means that underground cables are always thermally limited as compared to overhead lines that may have thermal limits, surge impedance loading limits or stability limits.

Cable circuits have lower positive sequence (series) and surge impedances as compared to similar overhead lines. As such, they will tend to carry more load when operating in parallel with an overhead line. Also, due to the significant amount of capacitance in the cable, switching transients must be considered carefully. Ferranti effect (voltage rise) in lightly-loaded cables is uncommon, but dense urban cable-using utilities often consider shunt reactors.

Unlike overhead lines where faults can be temporary, cable faults are permanent. This must be considered when setting protective devices for operation on hybrid lines.

D. Power Transfer Capability

Cables generally have much lower ratings than comparable overhead lines. This has to be considered when using cable in a network of underground and overhead lines and when designing hybrid circuits – lines that have segments of both overhead and underground – so that the cable does not limit the capacity. Buried power cables have long thermal time constants of 30-100 hours, and this characteristic permits cables to have very high emergency ratings as a percentage of normal ratings; therefore, cables may be limiting under normal conditions, but overhead lines could be limiting during emergencies. Daily load cycles are considered for normal ratings on cable circuits to account for the long time constant.

E. Operation & Maintenance

Cable systems are largely immune from weather effects; this significantly reduces the impact on maintenance requirements and enhances reliability from unplanned outages. Cable terminations must be checked for contaminants or mechanical damage, cable jackets are periodically tested for damage or degradation, and bonding cables must be checked for corrosion. HPPT and SCFF cables, because of their hydraulic systems, require more extensive maintenance including frequent checks of pressurization plants and fluid reservoirs and monitoring for leaks. Thermal-mechanical movement of cables in conduits and pipes must be properly managed, particularly where there are significant elevation changes or large-diameter extruded cables in conduits. Periodic analysis of dielectric oils must be considered to assess paper cable condition.

F. Repair

Cable failures are less common than for overhead lines but they do occur. Because most of an underground cable system is inaccessible, fault location can slow the restoration process. A transmission cable may require 2-3 weeks (sometimes longer) to repair once the failure has been located and all necessary materials and specialized technicians are available. Managing the dielectric oil in HPFF cables during repairs often requires expensive freezing of the oil on either side of the failure using a system of copper tubing and liquid nitrogen to create a hydraulic stop; this lengthens repair time.

Restoration of a transmission cable could take more than a month. Lead times for replacement transmission cables and accessories can be 4-6 months or longer, so some utilities using these systems often maintain spares.

G. Cost & Economics

The installed cost of underground cable systems is generally 3-10 times that of comparable overhead lines. However, rights-of-way costs are typically much less than for overhead lines, and underground lines generally have a lower perceived environmental impact making the permitting process easier, faster and often less expensive compared to overhead. Cost of losses in cables are generally lower than for overhead lines, but reactive compensation and charging current losses must be considered.

IV. REQUIRED DESIGN STUDIES

A. Ampacity & Soil Thermal Testing

Buried cable ratings are modeled by considering heat transfer by thermal conduction from the conductor, through the cable layers and soil to ambient earth. Copper cables have ratings approximately 30% greater than comparably-sized aluminum conductors. Soil characteristics are carefully studied as part of the cable design to determine the ability for heat to pass through the soil; *in situ* field testing as well as laboratory evaluation of collected soil samples and mix designs for specialized thermal backfill (FTB, etc.) are performed. Burial depth, ambient soil temperature, and spacing among cables, circuits and other heat sources are all carefully considered in selecting the cable conductor size, number of cables per phase, etc. Dielectric heating from charging and discharging the insulation capacitance at power frequency raises the cable temperature and affects ampacity. Heat losses from shield/sheath bonding configurations, cable pipes, and armor on submarine cables are all factored into the calculations.

B. Pulling Tension

Many cable systems, often in urban environments, are installed in conduits or pipes. Civil work to install the infrastructure is completed first and the cables are pulled in later. Calculations are done to evaluate the pulling forces that will be experienced by the cables during installation. Concerns over exceeding these forces, both longitudinal limits and sidewall bearing pressures, are factored into the placement of vaults and selection of pulling lubricants. When multiple cables are pulled into the same conduit or pipe, pulling forces are shared among conductors.

C. Electric & Magnetic Fields

Shielded power cables do not have any external electric fields by virtue of the shield on the outside of the insulation. Lower magnetic fields are often cited as a reason to justify using underground cables instead of overhead lines, usually because of epidemiology or magnetic interference concerns. Cables generally have lower field levels than overhead lines because of the closer phase spacing (9-12in, 230-300mm) that attenuates the external magnetic flux density. The pipe in a pipe-type cable provides magnetic shielding.

As with overhead lines, field levels are usually evaluated at 1m (3.28ft) above ground. While the wide phase spacing of overhead lines usually results in higher magnetic flux density, cables are often installed only 30-60in (0.75-1.5m) below ground; the closer proximity to the point of calculation/measurement means that when standing directly above the underground cable right-of-way, field levels may be higher for underground. Methods to mitigate underground cable magnetic fields may be considered during the design. Figure 5 illustrates comparable field levels for overhead and underground cables.

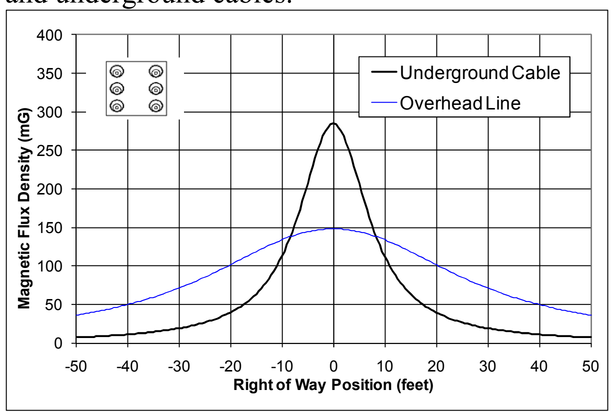

Figure 5: Comparison of underground cable and overhead line magnetic field levels.

D. Induced Voltages & Currents, Bonding

The connections of the metallic shield, sheath and, if present, armor in extruded and self-contained cables must be considered for many reasons including ampacity and induced currents and voltages. Multiple-point bonding is common with distribution voltage cables and submarine cables but uncommon for most high voltage systems because circulating current losses reduce ampacity by 30%. Single-point bonding, where the shield is grounded at only one location, is used for short circuit lengths but can result in high standing sheath voltages and several kilovolts during faults; this can damage the jacket. Cross-bonding is often used on transmission cables to manage circulating currents and induced voltages but requires special bonding boxes. The impact of ground continuity conductors must also be considered. These are all evaluated using extensive numerical analyses to determine voltages across joint shield gaps, sizing of sheath voltage limiters, and induced effects when a de-energized cable circuit must be serviced while a parallel cable system remains energized.

E. Fault Current Capability

Sizing the metallic shield and sheath of a cable to withstand available fault current is important so that cable is not unnecessarily damaged during a through-fault. Adiabatic conditions are often assumed with most calculations for the short time (0.06-0.5 seconds) required for circuit protection to operate; "stuck breaker" clearance times may be considered.

F. Hydraulics

Hydraulic calculations are important for HPFF and SCFF cable systems. Fluid reservoirs for SCFF cables must be sized and located to maintain fluid pressures within operating limits. HPFF cables have specialized pressurization plants that actively handle dielectric oil thermal expansion and contraction and maintain proper oil pressures. Hydrostatic pressure differences from variations in elevations along the cable routes must be managed through proper settings, and oil circulation pumps may be used to mitigate thermal hot spots. The time required to locate leaks is factored into sizing pumping plants and fluid reservoirs.

G. Corrosion

Corrosion is primarily a concern for pipe-type cable systems, specifically regarding the cable pipe; corrosion protection has been considered for the armor of a few submarine cables. The cable pipe is essential for the reliable operation of HPPT systems, so insulated coatings are used on the outside of the cable pipe. To address possible coating holidays or damage, an impressed current cathodic protection system is used to put -0.85Vdc on the cable pipe, sometimes supplemented by sacrificial anodes (zinc, etc.) along the pipe. The pipe is normally grounded through a polarization cell or solid-state isolator surge protector (ISP) which supports the applied dc cathodic protection voltage, but dissipates ac fault current to ground during an event.

H. Temperature Monitoring Systems

Temperature monitoring of key locations along cable routes has been done for many years using thermocouples or thermisters. While inexpensive, robust and easy to monitor, these discrete measurements may miss hot spots. In the last decade or so, distributed temperature sensing (DTS) using fiber optic cable has become common. A fiber installed nearby the cable in a parallel conduit, sometimes attached to the cable or pipe surface or put under the jacket may record temperatures along the cable circuit once every meter or so for the length of the line. As-built ampacity calculations and identifications of hot spots are permitted through periodic testing, and continuous monitoring can serve as the basis for dynamic/real-time rating systems.

V. CONSTRUCTION METHODS AND INSTALLATION

A. Open Cut Trenching

Open cut trenching using an excavator is the most common method for installing underground power cables. Direct buried installations require that long sections of trench remain open until cable laying is performed. For this reason, cable pipes or conduits installed in duct banks are most often used for urban settings. Fifty feet (15m) of trench can be open, ducts or pipes installed, and the trench backfilled with a fluidized thermal backfill (FTB, concrete encasement) or thermal sand (granular backfill). The surface can then be restored (re-paved, etc.).

Spare conduits are often installed to accommodate future cable circuits, the possibility of an installed conduit becoming unusable, for ground continuity conductors or to support communication lines. Typical trenches are 2-4 feet (0.6-1.2m) wide and usually at least 4ft (1.2m) deep.

Figure 6: Open-cut trenching for duct bank installation

B. Trenchless Technology

In locations where open trenching is infeasible, pipe-jacking (jack-and-bore), microtunneling or horizontal directional drilling (HDD) may be used and then transitioned to open-cut trenched sections. Pipe jacking and microtunneling involve excavating pits on either side of the obstacle to be crossed under (often rail lines or roadways); typical lengths are 100-300ft (30-100m). In these methods, a casing pipe made of steel or reinforced concrete is pushed through while open face excavation or an auger is used to clear the path; steering is not possible.

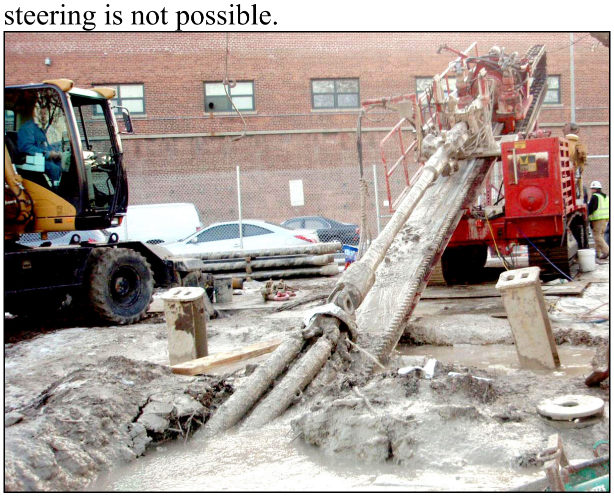

Figure 7: Horizontal directional drilling for conduit bundle

HDD is launched from the surface at a shallow angle (no deep pits required) with a small (~6in, ~152mm) pilot hole boring under the obstacle (river or other body of water, environmentally sensitive area, etc.) and the steel or high-density polyethylene casing pipe back pulled after sufficient borehole reaming; conduit bundles or cable pipes may also be installed without using an outer casing (e.g., a "slick" bore). Distances are often limited by cable shipping or pulling lengths. Using HDD to install the conduit or pipe, extruded cables have been installed up to 2,000ft (600m), while pipe cables have been installed up to 7,400ft (2.3km). Significant geotechnical and civil design studies must be performed, and the lay down area is extensive for mud handling equipment and for assembling the casing, conduit or cable pipe.

C. Submarine Cable Laying

Submarine cable installations of extruded or self-contained cable require careful planning and often extensive geotechnical studies, coordination with marine authorities and permitting. Basic cable designs are similar to land cables; armor wires and serving are often added to support the cable during installation and retrieval if a repair is necessary. The metallic sheath and/or concentric neutral may be oversized to limit circulating currents losses. Due to the lengths involved, most submarine installations are multiple-point bonded to manage standing shield/sheath voltages.

Cables are loaded on to laying ships or barges in long lengths, if possible, avoiding the need for splice points in the water; SCFF cables have an advantage in this regard. During installation, cable is paid off the laying vessel and either laid directly on the sea floor or, using a plow on the water bottom, embedded up to 15ft (5m) depending on conditions and project requirements. Cable end sections are floated to shore for substation connections or splices on land.

Figure 8: Submarine cable laying barge

D. Aerial & Tunnel Installation

Insulated power cables may also be installed in air within substations or inside station buildings, though this is not common at transmission voltages. Solar heating and wind effects, similar considerations as for overhead lines, must be evaluated when determining ratings for in-air cables.

Some of the first 500kV extruded and SCFF cables were installed in tunnels with cables suspended from tunnel walls with clamps, placed on the tunnel floor or embedded in sand or other material under the tunnel floor. Ventilation and air handling equipment to manage air temperature within the tunnel is often a consideration, and common-mode failure of multiple circuits in the event of a fire should be evaluated.

E. Cable Pulling

After conduits or pipes are installed, cable pulling can be performed. Weather conditions and equipment trials must be evaluated prior to commencing a cable pull. A mandrel that is slightly smaller (3/8in, 9.5mm) than the inner diameter of the conduit or pipe is passed to check for obstructions or damage; swabs may also be passed through for cleaning before using a tag line to pull the pulling rope, often 1-1/8in (29mm) special steel line, through the conduit or pipe to attach to a pulling eye on the cable conductor (basket-type grips are not commonly used on transmission cable). A special yoke is used to connect the pulling line to the three pipe-type conductors for simultaneous installation. Lubricant is applied to the cables during pulling to minimize pulling forces, and tension is monitored and recorded with a dynamometer to ensure allowable tensions are not exceeded. Reel brakes may be used to avoid cable over-runs, but back tension must be managed carefully to avoid excessive pulling forces.

Direct buried cables are usually pulled over rollers spaced every 4-6ft (1.5m) in the trench; tensions are usually low and not of much concern but care must be given to avoid mechanical damage to the cable jacket.

After pulling, pipe cables have a night cap bolted to the flange and sealed; a short vacuum procedure to remove moisture is then applied before filling with a small positive pressure of dry nitrogen gas until the cables are ready for splicing or terminating.

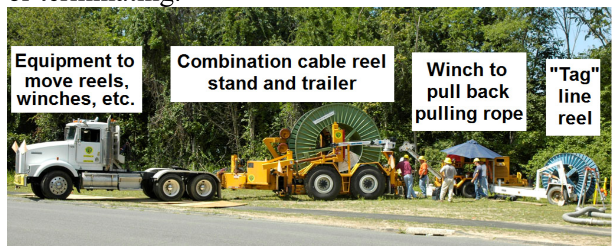

Figure 9: High voltage extruded cable installation

F. Splicing

Connecting two adjacent power cable sections together requires a splice (joint). Joints are larger in diameter than the cables they connect because of additional insulation material to manage electrical stress and facilitate building the joints in the field. For modern extruded cables, cable ends are prepared and a pre-molded joint body is pushed over the cable ends. The shield/sheath bonding connections are made to a link box, and the hermetic seal of the cable is restored.

HPPT and SCFF cables require that rolls of hand-applied paper tapes be placed over the prepared cable ends after a connector has been installed. Hydraulic continuity, as well as the internal positive pressure, must also be considered with these cables. Semi-stop or full-stop joints may be used to limit or block hydraulic flow. Bonding connections are used on SCFF joints, similar to extruded cables. Pipe-type cables must have steel sleeves welded over the 3-phase joint and to the pipe ends prior to pressurizing with dielectric oil or dry nitrogen gas.

G. Terminating

Cables are connected to other equipment using terminations (potheads or sealing ends) that manage the transition between the high-dielectric strength cable insulation and low-dielectric strength air while also preventing moisture and contaminants from entering the cable and, for HPPT and SCFF cables, containing positive internal pressure. The cable ends are prepared, paper rolls (HPPT or SCFF) or pre-molded stress cones (extruded) are applied over the cable, and a porcelain or polymer termination body is installed.

The base plate of the termination is isolated from the support structure to manage circulating currents and allow (for HPPT) a cathodic protection voltage to be applied to the cable pipe. Bonding cables on extruded and SCFF cables are connected through link boxes to permit jacket integrity testing.

VI. TESTING

A. Qualification (or Type) Tests

Usually associated with extruded cables, these tests are done by a manufacturer to prove compatibility between a particular cable design and joints and terminations to be used with the system. This test requires a few months to setup and administer and is often monitored by a certified testing authority. Utilities usually want a successful test report from an "essentially similar" cable prior to making a purchase.

B. Factory Acceptance Tests

Factory tests are performed on a customer's cable to verify that it has successfully been manufactured to specifications and should perform as expected after installation. Industry specifications designate the types and frequencies of tests to be performed. Factory acceptance tests include routine (production) tests performed on every length of cable leaving the factory and sample tests that are performed on selected pieces of cable from the same production run. Tests include dimensional checks, mechanical performance, cable component electrical characteristics, and high voltage withstand.

C. Commissioning Tests

After completing the works to install a cable system, commissioning tests are done to verify the integrity of the installed cable system. These include voltage withstand tests, sometimes using available system voltage or variable frequency resonant test equipment, along with pipe coating and cable jacket integrity tests.

D. Diagnostic Tests

Testing on installed cable systems can be done on existing circuits and may include fault location to find a failure, or cable system condition tests such as dissolved gas-in-oil analysis, partial discharge detection,dissipation factor measurement or periodic jacket integrity tests.

VII. CONCLUSION

With proper consideration of the many factors related to design, specification, manufacturing, installation, and commissioning, underground cable systems can be a viable alternative to overhead lines where the use of cable is warranted because of rights-of-way constraints, sensitive areas along the planned route, specialized obstacles (waterways, bridges, etc.) that must be crossed, concerns about weather effects and reliability affecting overhead lines, or clearance limitations to get into a congested substation. Though the material and installation costs of underground power cables are higher than comparable capacity overhead lines, factors such as real estate, permitting and constructability can often make underground the preferred alternative as a complete underground system or portions of a hybrid underground and overhead circuit.

VIII. REFERENCES

[1] E.C. Bascom, III, D.A. Douglass, et. al., "Hybrid Transmission: Aggressive Use of Underground Cable Sections with Overhead Lines", CIGRE 1996, SC 21/22-10.

[2] J.H. Neher, M.H. McGrath, "The Calculation of the Temperature Rise and Load Capability of Cable Systems", AIEE Insulated Conductors Committee, June 1957.

[3] IEC-60287, "Calculation of the Continuous Current Rating of Cables (100% Load Factor)", International Electrotechnical Commission, 1994.

[4] IEEE Standard 835-1994, "Standard Power Cable Ampacity Tables".

[5] IEEE Standard 442-1981, "Guide for Soil Thermal Resistivity Measurements", 1981, 1996.

[6] R.C. Rifenberg, "Pipe-Line Design for Pipe-Type Feeders", AIEE Transactions, Vol. 9, December 1953.

[7] "Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (Up to 300GHz)", International Commission on Non-Ionizing Radiation Protection, 1998.

[8] E.C. Bascom, III, et. al., "Considerations and Approach to Mitigating Underground Cable Magnetic Fields", Proceedings of 2nd CIGRÉ-SEE EMF-ELF Conference, Paris, France, 24-25 March 2011
[9] IEEE Standard 575-1988, "Guide for Bonding Sheaths of High-Voltage Single-Conductor Power Cables".
[10] W.A. Lewis, G.D. Allen, "Symmetrical Component Circuit Constants and Neutral Circulating Currents for Concentric Neutral Underground Distribution Cables", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, January/February 1978.
[11] E.C. Bascom, III, et. al., "Taking Your Cable's Tempearture", T&D World Exposition, May 2002, Indianapolis, IN.
[12] AEIC CG4-97, "Guide for the Installation of Extruded Dielectric Insulated Systems Rated 69kV Through 138kV", January 1997.
[13] "IEEE Guide for Installation of Cable Using the Guided Boring Method", 1333-1994.
[14] IEEE Standard 1120-2004, "Guide for the Planning, Design, Installation, and Repair of Submarine Power Cable Systems".
[15] ICEA S-108-720, "Standard for Extruded Insulation Power Cables Rated Above 46kV Through 345kV", 2004.
[16] AEIC CS9-06, "Specification for Extruded Insulation Power Cables and Their Accessories Rated Above 46kV Through 345kV AC", Association of Edison Illuminating Companies, 1st Ed.
[17] AEIC CS2-97, "Specification for Impregnated Paper and Laminated Paper Polypropylene Insulated Cable High-Pressure Pipe-Type", Association of Edison Illuminating Companies, 6th Ed.
[18] IEC 60840, "Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 30kV (Um=36kV) up to 150kV (Um=170kV) – Test Methods and Requirements", April 2004.
[19] IEC 62067, "Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 150kV (Um=170) up to 500kV (Um=550kV) – Test Methods and Requirements", Edition 1.1, 2006.
[20] "IEEE Guide for Fault-Locating Techniques on Shielded Power Cable Systems", 1234-2007.
[21] E.C. Bascom, III, D.W. Von Dollen, H. Ng, "Computerized Underground Cable Fault Location Expertise," IEEE PES Transmission & Distribution Conference, Spring 1994.

IX. BIOGRAPHIES

Earle C. (Rusty) Bascom, III holds an A.S. in Engineering Science from Hudson Valley Community College, Troy, New York, a B.S. and M.E. in Electric Power Engineering from Rensselaer Polytechnic Institute, Troy, New York, and an M.B.A. from the State University of New York at Albany. Mr. Bascom began his career in 1990 working with underground cable systems at Power Technologies, Inc. and, later, Power Delivery Consultants, Inc. before founding Electrical Consulting Engineers, P.C. in 2010 where he is a Principal Engineer. There, Mr. Bascom performs engineering studies and design for underground and submarine cable systems involving cable system assessment, advanced ampacity and uprating studies, preparing system specifications, performing quality assurance inspections during manufacturing and installation, magnetic fields evaluations, forced cooling and rapid circulation calculations, and economic evaluations of underground and submarine cable systems. Mr. Bascom is a Senior Member of the IEEE, Power & Energy Society, a Voting Member of the Insulated Conductors Committee and Standards Association, a member of CIGRÉ, and a registered professional engineer in New York, Florida and Texas. He can be contacted at r.bascom@ec-engineers.com.

Victor D. Antoniello holds a B.S. in Electrical Engineering from the University of Maine and an M.S. in Electrical Engineering from Northeastern University. Mr. Antoniello worked for 17 years at New England Electric (now National Grid) where he developed engineering and operation experience with underground transmission and distribution systems. He continued focusing on underground cable systems while working at Power Delivery Consultants, Inc. for 6 years before co-founding Electrical Consulting Engineers, P.C. in 2010 where he is a Principal Engineer. Mr. Antoniello has extensive experience with design, analysis, installation and operation of underground pipe-type, SCFF, and extruded cable systems. He is a member of the IEEE, its Power & Energy Society, Insulated Conductors Committee and Standards Association. He is a registerd professional engineer in Rhode Island, Massachusetts and New York.