Design and Other Technical Considerations for Applying Cross-Linked Polyethylene Transmission Cable to Retrofit into Pipe-Type Cable Pipes

Earle C. (Rusty) Bascom, III, Senior Member
Electrical Consulting Engineers, P.C.
Mesa, Arizona, United States

Sara E. Lacey, Non-Member
Charles S. Schupler, Non-Member
William A. Lopez, Member
PEPCo, An Exelon Company
District of Columbia, United States

Shoji Mashio, Non-Member
Satoshi Ona, Non-Member
Sumitomo Electric Industries, Ltd.
Japan

Abstract — **A North American utility has extensive pipe-type cable on their system. While reliable, utilities recognize that long-term industry trends are to use extruded dielectric cables exclusively as pipe-type manufacturing capabilities and qualified contractors are diminishing in the industry. Extensive infrastructure for pipe-type cables is already present at many utilities, which would be costly to replace, so one utility considered a project that would use extruded cable installed in a pipe to evaluate practical aspects of retrofit applications while gaining operational experience. This paper discusses and identifies the challenges encountered by the utility's design team, describes the selected cable system, and summarizes the project details.**

I. Introduction

Utilities in North America have utilized pipe-type cables for nearly 90 years. During this time, the oil-impregnated kraft paper insulation and, later, laminated paper-polypropylene insulation have provided long-term reliability and good operating history. However, extruded cable technology – in particular, cross-linked polyethylene ("XLPE") – has matured during the last quarter of the 20th Century and is generally regarded as having lower maintenance and avoiding the oil pressurization systems and the inherent dielectric oil associated with pipe-type cables. Worldwide manufacturing resources for paper-insulated cables have also diminished significantly with only one pipe-type cable supplier remaining such that utilities consider this a security risk from the low diversity of supply, while also facing limits on spare parts and diminished availability of personnel and contractors able to work on these cable system types.

However, the installed cable pipes represent a significant capital investment for utilities using these systems. While the paper cables potentially may not have long-term viability, the cable pipe remains a viable conduit if there are suitable cables – XLPE or otherwise – that can be installed in the pipe and allow for the existing power transfer capacity to be maintained or increased.

Recognizing that the eventual replacement of failed pipe-type cable or modifications to the existing pipe-type system might not be possible in the future, the Potomac Electric Power Company (PEPCo, An Exelon Company) endeavored to evaluate XLPE-insulated cable retrofit options for the utility's extensive network of cable pipes. This pilot project was part of a relatively short (550m, 1800ft) segment of a planned urban transmission reinforcement project in the District of Columbia (Washington, D.C.). Initially, the cable system is to be operated at 138kV, but planned future system modifications would have this circuit operate at 230kV so the retrofit options needed to be designed for 230kV operation.

The paper describes the technical considerations employed by the utility and their design team, summarizes industry available options for retrofit and the selected alternative for this project, and provides some details of the actual installation.

II. Alternative Cable Design Approaches

Various options of extruded cable retrofit are possible and available commercially. There are four basic alternatives that are technically viable, as follows:

A. *Separate Cables on Separate Reels*

This design uses conventional single-core XLPE cables transported with each phase on a separate reel, and the reels pulled into the pipe together. Using this approach has the benefit that longer lengths may be transported for installation since each phase is separate. However, the cable outer diameter tends to be slightly greater because each phase may have its own metallic sheath and concentric metallic shield. During cable pulling, two of the three cables would be assumed to carry the tensile pulling force. Depending on the outer cable diameter and inner pipe diameter, the cables may not be in optimal triangular (trefoil) configuration, which can increase losses and limit the rating.

B. *Bound Cable Cores with Common Reinforcing*

Another option for retrofit cable is a "belted" design with the three cable phases constructed using an individual metallic shield tape and insulating jacket but with a surrounding belted armor that provides mechanical strength for pulling. The belted design allows that all three cables can share the pulling force. The first commercial applications of this type were for retrofit options in Europe; the splice spacing and pulling sections lengths were generally short (200-250m) compared to typical U.S. pipe-type cable sections (450-900m) so shorter transportation lengths were acceptable. Due to the combination of the three cable cores in one cable, the allowable transportation length may be constrained as compared to transporting a single phase cable.

C. *Three-Core Cables*

Three-core extruded cables have been used for many years, sometimes for retrofitting three-core self-contained fluid-filled cable circuits. The advantage with these designs is that a common metallic moisture barrier (sheath) and jacket can be put around all three cable cores, and ground continuity conductors may be integrated in the interstices between power cable cores. However, present technology is generally limited to distribution or sub-transmission applications so available technology was not suitable at the time of this project. Like with bound cable cores with reinforcing, the physical size of this cable may limit transportation lengths using surface transportation.

D. *Triplex Three-Core*

This is a hybrid of the single-core and belted three-core cable designs. The cable is manufactured with individual cores including a metallic sheath and plastic jacket. However, the three

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cores are tri-plexed on to a shipping reel and are installed together; all three cores share the pulling forces. Additional ground continuity conductors or conductive tubes may be included with the power cables to provide ground continuity conductor functions; the size and number of conductors can be adjusted to meet fault current requirements. The combined three phases in the triplex design may limit maximum transportation lengths due to the weight or physical size of the cable reel. Figure 1 shows an example of this cable design without any auxiliary elements (ground continuity conductors or optical fibers).

For the project described in this paper, the triplex three-core design was selected.

Figure 1: Example triplex XLPE transmission cable

III. TECHNICAL CONSIDERATIONS FOR RETROFIT

Underground transmission cables have been used for electric power applications for more than 100 years, and the basic technologies involved – paper-insulated pipe-type cable and XLPE-insulated extruded cable – are supported by industry practice, analysis techniques and standards. However, the unique aspects of putting XLPE-insulated cable into a previously-installed cable pipe have nuances that were considered, as follows.

A. Ampacity Impact: Pipe-Type to XLPE Cable Conversion

Cable ratings (i.e., "ampacity") are routinely calculated using methods from the 1957 Neher/McGrath paper and IEC 60287 rating standards for pipe-type cables. However, the construction of extruded cables – usually with a relatively lower resistance concentric metallic screen and sheath and an insulating jacket – differ from conventional pipe-type cable and, therefore, the calculation of ratings are treated differently. Specifically, the ratings must consider that the individual cable shields are insulated from one another, and the relative positions of the cables within the pipe would impact the pipe hysteresis and eddy current losses. The cable pipe effectively becomes a casing from the standpoint of installing extruded cables. For the rating calculations, the casing losses were extended from work done in the 1970s and 1980s with consideration of the installation conditions used for the pipes[3]. The loss increment in the casing, Y_{Casing}, is determined using an equation of the following form:

$$Y_{Casing} = \frac{4}{3 \cdot \pi \cdot r_{dc} \cdot D^2 \cdot \sigma_{Casing}} \cdot Z_{Casing} \sum_{n=1}^{\infty} |Y_n|^2 \left(\frac{-4 \cdot Q_{n,2}}{F_n} \right)$$

In the above equation, F_n is a function calculated using Bessel functions included in the arguments of the summation, and Z_{Casing} is a geometric factor for the casing that includes the magnetic permeability of the steel casing pipe, both of which are developed as detailed in the reference [3]. The conductivity of the casing is represented by σ_{Casing}, D is the casing diameter, and r_{dc} is the resistance of each power cable conductor. This methodology was used to determine pipe losses for ampacity calculations. The other aspects of the cable ratings followed the conventional rating methods.

Aside from the calculation method, a big challenge for retrofit of extruded cables into a cable pipe is matching or maintaining the cable rating. A major contributing factor is the insulation dielectric strength of pipe-type cables as compared to XLPE-insulated cables as illustrated in Table I. The generally greater required insulation thickness needed for XLPE cables is a retrofit challenge. Due to the thicker insulation wall and usual application of a thick extruded plastic cable jacket on an XLPE cable, the overall cable diameter of an extruded cable is significantly greater than that of a pipe-type cable. Therefore, the options for selecting a larger conductor size or incorporating a voltage upgrade in conjunction with a retrofit are sometimes limited. To offset the typical insulation thickness, manufacturers are working to develop higher stress cable and accessory designs (i.e., lower insulation wall thickness) to permit more retrofit options.

TABLE I - TYPICAL INSULATION WALL THICKNESSES FOR MODERN TRANSMISSION CABLE

Voltage	Paper[4]*	PPP[4]**	XLPE (typical)
69kV	7mm (0.270in)	Not Available	9.0-15mm (0.36-0.59in)
138kV	12mm (0.440in)	8mm (0.30in)	15.2-18.0mm (0.60-0.71-in)
230kV	19mm (0.750in)	12mm (0.44in)	21.6-23mm (0.85-0.92in)
345kV	23mm (0.905in)	16mm (0.60in)	26-30mm (1.05-1.20in)

* "Paper" refers to oil-impregnated kraft paper insulation.
** "PPP" is an abbreviation for paper-polypropylene-paper taped insulation.

B. Pipe Preservation Considerations

A major design consideration for retrofit applications of extruded cables is if the pipe must be protected and preserved or if the pipe will be allowed to experience degradation (principally from corrosion). The cable pipe in a conventional pipe-type cable system is completely sealed with welded casing sections, positive internal pressure (oil or nitrogen gas), a corrosion coating on the exterior of the pipe and an impressed-current cathodic protection system because the pipe is integral to the continued operation of the cables.

With extruded cables, the conduit or pipe in which the cables are installed is impertinent to the operation of the extruded cable aside from facilitating replacement between accessible points (manholes or riser structures). In particular at splice locations, the conduit ends are not connected across the manhole to facilitate splicing. With a retrofit of extruded cable, the pipe ends within the manhole could be left open to facilitate splice installation on a manhole wall, but this would permit water, contaminants, and possibly insects or animals to enter the pipe and would allow general corrosion to occur on the interior of the pipe. Galvanic corrosion on steel is generally slow but could result in deterioration of the pipe over the typical 30-40 year expected life cycle of a transmission cable system. Also, with the pipe ends exposed, an impressed current cathodic protection system cannot function since the pipe is not continuous from terminal to terminal or fully insulated from ground.

If the pipe is to be preserved, the locations where the cables exit the pipes must be sealed from the environment and electrically insulated from local ground while providing electrical continuity across the pipe ends. Since the plastic jacket on an extruded cable is not completely impervious to moisture, the

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method to seal the cable ends has to be carefully designed. The sealing system and maintenance of the cathodic protection system will also impact the sheath bonding configuration.

C. Sheath Bonding Options and Bonding System Design

Extruded transmission cable sheaths are usually cross-bonded or single-point bonded to reduce or eliminate concentric metallic shield/sheath circulating currents that would otherwise reduce the cable ampacity by 20-40%. These special bonding configurations require interruptions in the electrical connections of the sheath to allow the bonding leads to connect to a link box. Furthermore, single-point bonding configurations require one or more ground continuity conductors to provide a low-impedance path for zero sequence current during a fault, both to dissipate the fault energy and so relay protection can detect the fault to operate circuit protection.

In a conventional pipe-type cable, the pipe itself provides a high-capacity path for fault current. However, with the extruded retrofit in place, the pipe would not necessarily have metal sleeves across the joint so there would be an interruption in the electrical path. Therefore, two options must be considered:

- **Bonding Connections to Pipe** – In this configuration, the pipe ends on either side of the joint would be electrically connected using a cable bonded to the pipe (and insulated from the environment if cathodic protection will be used on the pipe).
- **Cable Design with Integrated Ground Continuity** – The extruded cables used for retrofit must include either sufficient cross-sectional area in the concentric metallic shield/sheath (usually undesirable because the overall cable diameter is consequentially increased) or one or more additional ground continuity conductors pulled in with the power cables. The pipe itself may not need to be electrically included in the circuit for grounding purposes provided that the integrated ground continuity conductor(s) are so designed to manage the fault currents.

A hybrid system using the pipe and additional ground continuity conductors could also be employed. Calculating the zero sequence impedance must consider all of the conducting elements in the ground path. If the cathodic protection system is to be maintained on the cable pipe, polarization cells or isolator surge protectors would still be required to support the cathodic protection voltage applied to the pipe during normal operation.

D. Splice Size, Manhole Dimensions and Manhole Spacing

Extruded cables inherently have physically larger splices than similar voltage pipe-type cables, and the corresponding manhole sizes reflect the splice sizes; Table II shows some typical dimensions. As a result, most extruded retrofit applications will have to consider expanding existing manholes to accommodate the corresponding cable splices and possibly adding a second manhole to isolate extruded cable splices and circuits where previously two pipe-type cable splices were in a common vault. Figure 2 shows an example manhole used by the utility for the project described in this paper.

TABLE II - TYPICAL MANHOLE DIMENSIONS

Voltage	Paper or PPP	XLPE
69kV	12-15ft	15-18ft
138kV	12-16ft	18-22ft
230kV	15-18ft	24-27ft
345kV	16-20ft	26-33ft

In addition to the physical size of the manholes, the longitudinal separation between manholes may also be a factor for retrofit applications with respect to installation distances. At least for the cable designs that incorporate all three cables phases, the weight and size of the cable will constrain the quantity of cable that can be transported (approximately one third of a single-core cable length). For example, if 900-1400m (3000-4500ft) of single-core extruded cable is a transportation limit due to weight and/or reel size, the cable designs incorporating all three phases would be limited to approximately 300-500m (1000-1700ft). Pipe-type cable manhole-to-manhole installation sections in North America are typically (450-900m, 1500-3000ft), so retrofit applications may need to consider installation of new manholes along the route due to the shorter allowable shipping lengths.

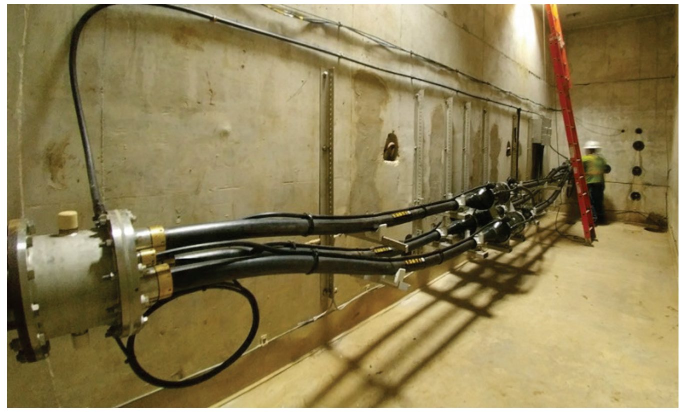

Figure 2: Example manhole for extruded-in-pipe prototype project.

E. Terminal Considerations and Trifurcator

The three pipe-type cables within a common steel pipe are separated near the terminal structures using a trifurcation assembly (as either a “pull through” or as a splice) to transition to separate stainless steel riser pipes. With the extruded cables retrofit within the steel pipe, a similar transition is required, ideally utilizing the same trifurcation. The typical stainless steel riser pipes used between the trifurcation and terminals are usually large enough to accommodate the extruded retrofit cables. However, some lengths of single-conductor cable may be needed for these installation sections since it would generally be impractical to separate the combined cables in any of the three-conductor cable designs for pulling. Figure 3 shows an above ground trifurcation assembly (sometimes called a “spreader head”) for the prototype project.

Figure 3: Trifurcation assembly for extruded cables with sealing system

F. Consideration to Prepare Pipe to Receive XLPE Cables

When planning to retrofit the cable pipe with plastic-jacketed cable, the pipe needs to be suitably prepared and inspected. As a first step, the existing pipe-type cables must be removed; usually, the utility or contractor will recover some of this cost from the metal salvage value in the cable system including the copper or aluminum conductor, the metallic tapes and the skid wires.

Aside from the cable removal, the dielectric oil must be removed. Usually, the oil will be drawn out using the pressurization plant pumps to the extent possible and then further drained using accessible taps at splices and terminals. The joint casings must then be opened and terminations removed so that the pipe-type cable itself can then be removed. The pipe can then be inspected by various tools and methods, swabbed and cleaned. A corrosion survey may also be done to further assess the integrity of the pipe and pipe coating before pulling new extruded cable.

IV. Cable System Details and Implementation

A. Prototype Project Description

The prototype project was selected by the utility as part of a series of urban underground transmission system reinforcement projects that included modifications to an existing substation and construction of a new substation. The prototype project was part of the electrical connection between the existing and new substation in the District of Columbia. The initial connections between the new and existing substations were to be made at 138kV but later reconfigurations would require the circuit to operate at 230kV. As a result, the project implementation required that all cables and accessories be designed to operate at 230kV.

While the planned circuit was going to be constructed new, the utility wanted to develop and implement this project in a manner that would simulate a true retrofit application of a 230kV pipe-type system. As a result, a 219mm (8-5/8in) carbon steel line pipe was installed using pipe-type cable practices including pipe sections with flared ends and backing rings (“chill” rings) that were welded together, and the corrosion coating restored. The total circuit length was approximately 700m (2400ft) with two intermediate manholes.

Two manholes were incorporated into the route allowing for two types of transitions; (1) one manhole had conventional cable pipes on both ends (see Figure 2) and (2) the other manhole had conventional pipe on one end and individual pipes on the other. The manholes were oversized to allow flexibility for the splicing while the utility and installer gained experience with the installation.

B. Cable System Design

As indicated earlier, a triplex cable design was selected for this project and was the result of a collaborative design by the utility’s design team and the selected manufacturer. Each cable core consisted of an approximately 659mm^2 (1300kcmil) compact round copper conductor, 19mm (0.748in) of cross-linked polyethylene (within the allowable insulation stress limit of 5kV/mm in accordance with AEIC CS9), copper foil laminate metallic sheath, and high-density polyethylene jacket with graphite coating. The ground continuity conductor system consisted of three (3) aluminum tubes and one (1) stranded copper conductor, all with XLPE insulation and graphite coating. The overall diameter of the completed cable was approximately 189mm (7.4in) with a weight of 37kg/m (25lbs/ft). Figure 4 shows an example cross-section of the completed cable.

Figure 4: Cable cross section for the pipe.

C. Construction and Installation Overview

The Washington, D.C. area is a dense urban center with a long history of construction including many underground utilities. The area in the vicinity of the construction included several existing underground transmission and distribution cable circuits, water and sewer lines and telecommunications infrastructure. In addition, the work on this project had to be coordinated with construction of a new substation and an overall schedule that included redevelopment of some nearby areas for public spaces, stadiums and other facilities.

The design team was actively working on the overall project for approximately four years, and construction and electrical installation took almost two years. Some of the design activities were complicated by changes to the planned redevelopment that was also ongoing during the utility’s project.

The electrical cable system installation had some typical challenges that are encountered during any major project including impacts related to weather and coordination between substation construction and underground electrical construction.

Commissioning was performed following Association of Edison Illuminating Companies (AEIC) recommendations including the use of a variable frequency resonant test set to apply 1.7x rated line-to-ground voltage (133kV for 230kV class system with a 226kV test voltage) and jacket integrity tests.[6]

Figure 5: Preparing for cable pull.

V. Conclusions

As the use of pipe-type cable diminishes in the industry, alternate extruded cables are available that can permit retrofit opportunities allowing utilities to retain the use of their valuable infrastructure. Additional technical development is still needed to further develop high-stress cable and accessories that will permit large conductors and greater current-carrying capacity while also affording longer installation distances.

The prototype project was successful, and the utility will gain operational experience for using extruded-in-pipe technology that will be invaluable for future applications.

VI. Acknowledgements

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VIII. BIOGRAPHIES

Earle C. (Rusty) Bascom, III (M’1989-SM’) holds an A.S. in Engineering Science from Hudson Valley Community College in Troy, New York, B.S. and M.E. degrees in Electric Power Engineering from Rensselaer Polytechnic Institute in Troy, New York, and an M.B.A. from the University of New York at Albany. Mr. Bascom began his career in 1990 working with underground power cable systems at Power Technologies, Inc. and, later, Power Delivery Consultants, Inc. He founded Electrical Consulting Engineers, P.C. in 2010 where as a Principal Engineer he continues to provide engineering services for underground and submarine transmission and distribution cable systems focused on the analysis, design, specification preparation, quality assurance inspections during manufacturing and installation, and evaluation of operational characteristics, including ampacity studies, condition assessments and failure investigations. He is a Senior Member of the IEEE, Power & Energy Society, Standards Association, Chair of the Insulated Conductors Committee, and the U.S. alternate representative to CIGRÉ Study Committee B1. Mr. Bascom is a licensed professional engineer in New York, Arizona, Florida, Texas, Delaware, Maryland and the District of Columbia. He can be contacted at r.bascom@ec-engineers.com.

Sara E. Lacey, P.E., holds a B.S. in Civil Engineering from the University of Maryland (2013) as well as a master’s degree in Engineering Management from Pennsylvania State University (2016). Mrs. Lacey is currently the manager of Underground Transmission Engineering at Pepco Holdings (PHI). She started her career in underground transmission engineering at PHI in 2013 and has served in several roles in PHI's transmission organization working on various initiatives from standards development to implementation of large underground transmission infrastructure projects. She has also previously held a role on PHI's regulatory compliance team as an engineering liaison to assist in the technical aspects of regulatory matters across various jurisdictions in the mid-Atlantic region. She currently serves as Chair of the North American Transmission Forum's Underground Transmission peer group. She is a member of ASCE and is a registered professional engineer in the state of Maryland. She can be contacted at SBishop@pepcoholdings.com.

William A. Lopez (M’2019) is the lead engineer and technical advisor in PEPCO’s transmission group and the project manager for special projects. He holds a BSCE degree from the University of Maryland and a master electrician license in Maryland and Virginia. Lopez worked for EMS Inc. as an environmental electrical control specialist for three years before joining PEPCO in 2000 as distribution engineer. He can be contacted at walopez@pepco.com.

Charles S. Schupler holds a B.S. in Civil Engineering from the University of Maryland (2011) and a Master of Science in Engineering Management from George Washington University (2013). Mr. Schupler joined the Potomac Electric Power Company, now PEPCO Holdings, in 2011 where he held various engineering positions in the overhead and underground transmission departments leading engineering projects involving overhead lines and cable and addressing operational issues. He is currently Manager of the Overhead Transmission Engineering Department and is a licensed professional engineer in Maryland. He can be contacted at csschupler@pepcoholdings.com.

Shoji Mashio earned a B.S. in Electrical Engineering from Tokyo University (1995) when he began his career at Sumitomo Electric Industries as a development and design engineer for EHV cable systems. Mr. Mashio has been working as secretary of CIGRÉ B1 panel in Japan from 2009 to 2014. He is currently General Manager, Global Project Engineering Department of Sumitomo Electric Industries, Ltd. He can be contacted at mashio@sei.co.jp.

Satoshi Ona holds B.S. (2007) and M.E. (2009) degrees in Materials Engineering from Osaka University. He began his carrier in 2009 at Sumitomo Electric Industries, Ltd. as an application system engineer for EHV cable systems including work on a 230kV XLPE submarine cable project in U.S. He can be contacted at ona-satoshi@sei.co.jp.