Novel Installation of a 138kV Pipe-Type Cable System Under Water Using Horizontal Directional Drilling

Earle C. (Rusty) Bascom, III
Senior Member
Electrical Consulting Engineers, P.C.
Schenectady, New York

Joseph Rezutko
Member
Florida Power & Light, Co
Juno Beach, Florida

Abstract — **While the power cable industry throughout the world is moving towards using extruded cable systems for most new ac cable projects, some North American utilities continue the use of high-pressure pipe-type (HPPT) cable systems for specific projects because of the long history of reliable operation using oil-impregnated paper and because the systems afford favorable conditions where long pulling lengths are required. This paper discusses the use of a unique cable design and application of horizontal directional drilling (HDD) to install nitrogen gas-filled HPPT cable under a marine setting in order to minimize the impact on the environment. The HPPT cable system permitted very long cable pulling distances of more than 1.6km, and was able to meet the utility's power transfer needs. The paper summarizes challenges that were encountered during design and construction of the project.**

I. Introduction

Florida Power & Light Co. (FPL) needed a new 138kV transmission circuit between Miami and Miami Beach, Florida to serve the increasing load and expand circuit redundancy for Miami Beach. The predominant feature between Miami and Miami Beach is Biscayne Bay, which includes a couple of small shipping channels and is an environmentally sensitive area. Due to aesthetics, technical limitations and the aforementioned environmental concerns there was no viable overhead route; as such FPL's transmission and siting departments were tasked with finding a viable route to traverse the bay that minimized the impact to Florida's protected sea grasses and other numerous environmental resources.

In 2006, FPL contracted to evaluate cable system and route alternatives for the lines. Both extruded (XLPE) and pipe-type cables were considered for the project, as well as a few different route alternatives. Construction methods also ultimately weighed on the selected route and cable system type.

This paper discusses the circuit and selected cable route, cable system design and summarizes the many challenges that were faced during construction.

II. Cable System Design Issues

A. Route Selection and Cable System Type

Various routes were considered between Miami and Miami Beach including the shoulder of an interstate and between small islands through a residential neighborhood. Both of these routes had difficulties with construction either by using directional drilling or open trenching. For the interstate route, directional drilling would have been required to go from the mainland to the causeway (narrow island) on which the section of interstate was built. The southern route had six small islands with predominantly residential housing and difficult locations for lay-down space for trenchless methods to connect or cross under the islands. A water route across Biscayne Bay was found to be the most viable alternative. This location also had some issues because it was considered an environmental sanctuary for marine animals and fauna. Any solution utilizing a water crossing could not consider open trenching or a conventional submarine cable lay as is often used in other parts of the world.

Cable system type also had to be carefully considered both for technical reasons and due to the stringent environmental restrictions. All of the possible routes would potentially require fairly long cable pulls that would likely exceed the allowable pulling tensions for extruded cable options (cross-linked polyethylene or ethylene-propylene-rubber). This effectively eliminated extruded cables as options for the project though they would offer a lower perceived environmental impact.

Typical pipe-type cables afford very long allowable pulling tensions because the cables share pulling loads during a pull, the coefficient of friction between the pipe and skid wire is low, and the cables themselves are smaller and weigh less. However, a dielectric oil-filled cable pipe would pose a potential environmental issue if the pipe were to be breached or develop a leak. High-pressure nitrogen gas-filled (HPGF) cable was selected as the preferred cable system because the nitrogen gas would be considering benign (it is 80% of the natural atmosphere), and there is a very low risk of the high-viscosity dielectric fluid contained in the insulation from leaking out of the cable pipe. The long allowable pulling distances would mean that only two cable splices would be required in the water with the bulk of the water crossing being installed by horizontal directional drilling. This was felt to offer the lowest environmental impact during construction and ongoing operation.

B. Cable Route and Construction Methods

FPL was seeking to connect its Overtown Substation in Miami with its Venetian Substation in Miami Beach. Overtown Substation is about 800m (0.5 miles) west of Biscayne Bay, and Venetian Substation is about 480m (0.3 miles) east of Biscayne Bay, both along busy city streets. The total route length was about 5.4km (17,650ft), with about 75% of it under Biscayne Bay.

Open cut trenching is the most common means to install underground power cables and is common to use under city streets. Horizontal directional drilling (HDD) is used for the installation of underground cables, as well as water, gas and telecommunication lines in difficult or restricted areas. Single HDD runs across the entire 4.1km (13,500ft) water crossing would have left cable pulls that exceeded allowable maximum tensions. Two long HDDs might have been possible, but the required setback meant that the drills would have exceeded the longest successful drill prior to that time. As a result, the design team decided that three 1.5-1.6km (5000-5500ft) horizontal directional drills would be done, requiring two

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splice points in the water. FPL had previous experience using HDD in the water for the relocation of 69kV and 138kV pipe-type cables near the Port of Miami back in 2001 [Ref. 1], so there was a high level of confidence that this approach would be successful. Figure 1 shows the location of the cable route.

Figure 1: Route map for 138kV pipe-type cable circuit.

C. Selected Cable System

Various cable designs were considered in an attempt to meet FPL's high line rating requirements. Compatibility with cable accessories (joints and terminations) and the higher required insulation thickness for the high-pressure gas-filled cable meant that the segmental copper conductor size was limited to 1520mm^2 (3000kcmil); at the time of the project, this was the largest HPGF cable manufactured to date. The Association of Edison Illuminating Companies (AEIC) CS-2 specification was used for guidance in developing other parameters for the 138kV cable. A summary of the major cable parameters is listed in Table I, and a desk sample of the completed cable system is shown in Figure 2.

TABLE I
DESCRIPTION OF OUTER CABLE LAYERS

Component	Description
Conductor, shield	3000kcmil, segmental, copper intercalated metalized paper and copper tapes
Insulation	0.585in., Kraft paper
Insulation shield	Intercalated metalized paper and copper tapes, and two layers of mylar tapes
Skid wires	2, 3in. lay, "D" –shaped (0.1in. by 0.2in.), stainless steel
Pipe Filling	Dry nitrogen gas
Cable Pipe	9-5/8in, 3/8-in wall

Figure 2: 138kV HPGF Cable with 3000kcmil segmental copper conductor and 9-in heavy wall cable pipe

A 219mm ($8^{5}/_{8}$ in.) Grade A steel cable pipe with 6.3mm (0.25 in.) wall thickness is commonly used for 138kV cable systems, with older higher-voltage cable systems using 274mm ($10^{3}/_{4}$ in.) cable pipe; these two pipe sizes are standard sizes available in the industry. Because the bulk of the cable pipe would be inaccessible after the installation in the directionally-drilled areas, use of a heavy wall 9.5mm ($^{3}/_{8}$ in.) steel pipe was desirable to provide additional wall thickness in the event corrosion attacked the pipe and due to the mechanical forces that would be encountered during pullback in the long HDD sections.

The selected cable size with the extra-thick insulation needed for the HPGF cable would not fit with adequate clearance inside the nominal 8-in pipe. Consideration was then given to using a nominal 10-in pipe but this presented two problems. First, the larger diameter pipe meant that the minimum allowable pipe bending radius for use during horizontal directional drilling was too large to meet the civil engineering requirements for the installation angles and depths needed on the project. Second, the cable jam ratio would have been very close to 3:1 with the larger pipe giving a strong possibility that the cables might jam during pulling.

Though non-standard, a nominal 9-inch pipe would be the right size for the project if it was available; this size would be small enough in diameter to permit the HDD installation to be performed and had the right diameter to provide an acceptable jam ratio for the cable during installation. Fortunately, a pipe supplier indicated that a non-standard 244mm (9-$^{5}/_{8}$ in.) heavy wall (9.5mm, $^{3}/_{8}$ in.) pipe could be manufactured with the flared ends and matching backing ("chill") rings if a sufficient quantity of pipe was ordered (a quantity consistent with total circuit length). Figure 3 shows the cable pipe. Because the pipe was to be used for an HDD application, the pipe's outer corrosion coating was a polymer concrete with fusion-bonded epoxy. Land sections of the cable installation could have been constructed with conventional 8-inch pipe with standard wall thickness, but the entire line – land sections included – was constructed using the 9-inch pipe.

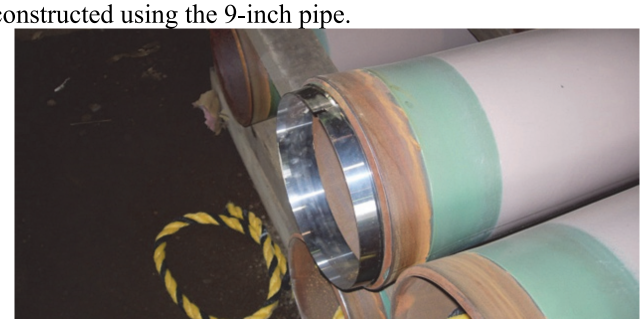

Figure 3: Unique 9-in heavy wall cable pipe with backing ring.

III. FIELD EXPERIENCE DURING CONSTRUCTION AND INSTALLATION

A. Route Construction and Trenched Sections

There were many challenges to the project as it progressed from design to commissioning. The permitting process was extensive because it involved many state as well as federal authorities and agencies including the Army Corp of Engineers and Department of Environmental Resource Management. The permitting process for obtaining soil samples alone lasted almost as long as the time to obtain permits to construct the project, or about 18-20 months.

The approach to construction was to have about 100m (300ft) of open cut trenching near the Overtown Substation, most of which was on substation property to a manhole located in the street just outside the substation. On the Venetian Substation side (Miami Beach), approximately 600m (1800ft) of open cut trenching was required through busy city streets. Special coordination was needed to minimize the impact on local businesses during this process.

Construction in the streets of Miami Beach was relatively straightforward except for the frequent rain showers that prohibited excavation progress and management of traffic patterns around the businesses.

B. Horizontal Directional Drilling Operation

Three horizontal directional drills (HDDs) were required; two between points on land and points in the water and one between two areas in the water. The HDDs were completed from barges, and later small platforms were configured in the water to facilitate cable pulling and splicing operations. Two barge setups were configured in the water; one approximately 1.8km (5,800ft) from a manhole near Overtown Substation, and the second about 1.6km (5,200ft) from a planned manhole on Miami Beach. This left the distance between the barges at approximately 1.6km (5,200ft).

Directional drilling (Figure 4) was more difficult than anticipated; the first HDD required nearly seven months for completion. Several issues affected the first drill, with the geology in particular proving to be particularly difficult. The limestone that was encountered was alternatingly porous and extremely hard which caused the drill stem to break on two separate occasions. The specialized equipment needed for tracking the HDD failed, further delaying the first drill while a replacement was obtained. Once the first drill was finally completed and properly reamed, the welds on the pipe pulling head failed. The welds had not fully penetrated the heavy pipe wall, so the pulling head separated from the cable pipe during pullback unintentionally allowing drilling mud and water to enter the pipe. There were also some unintended returns (sometimes called "frac-out") when the directional drill path, apparently by happenstance, crossed what was believed to be an old bore hole that had not been properly grouted or possibly an old artesian well.

Figure 4: HDD rig on Miami Beach

Many of the difficulties with the drilling mud were related to the geology. In addition to the mechanical stresses imposed on the drilling pipe, the porous nature of the lime rock allowed the drilling mud to leach from the bore hole, limiting the lubrication it normally offers to the product pipe during pull back. Ultimately, an "intersect" method was used to successfully complete the first bore. This method was utilized on the subsequent HDDs allowing them to be completed in a timely manner that was in line with pre-construction forecasts. The intersect method drills a bore hole from both ends with the drills meeting in the middle. One drilling head then follows the other back out to obtain a complete hole from end to end. This process significantly lessens the stress on each set of drill pipes and helps facilitate longer crossing distances.

To avoid interfering with boats, the cable pipe was welded and assembled on land and then towed out on floats to the pullback location on Biscayne Bay just prior to installation. In this way, the cable pipe could be fully assembled without blocking areas of the water for an extended period of time. The water was a convenient place for lay down area for the cable pipe during pullback, as shown in Figure 5. Figure 6 shows the lay down area for the directional drill operation from the eastern platform towards Miami Beach.

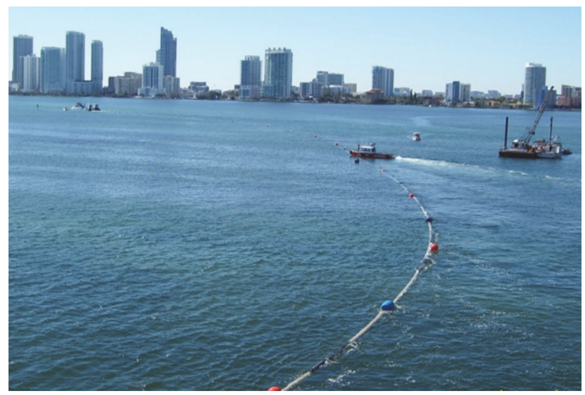

Figure 5: Floating cable pipe out to the platform for pullback

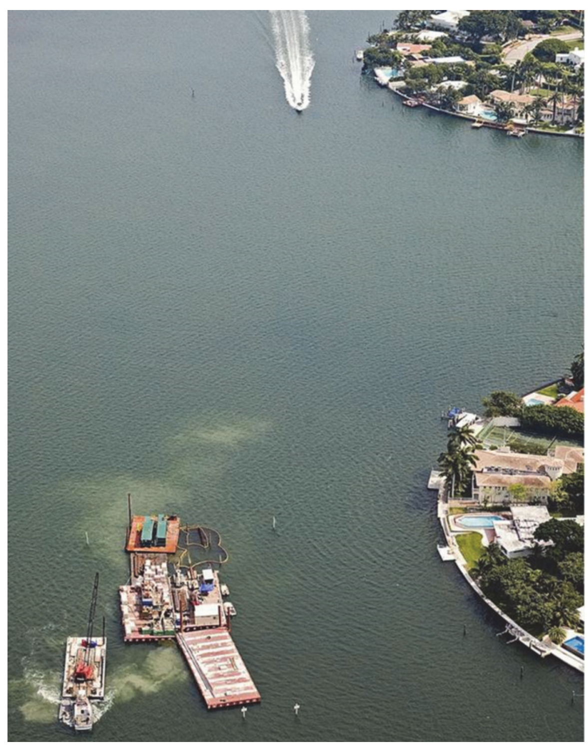

Figure 6: Directional drill from eastern platform towards Miami Beach.

The drilling mud that inadvertently entered the cable pipe during the pipe installation process later proved to be a problem in that it was difficult to get the water out of the cable pipe that had accumulated during flushing of the drilling mud. Ultimately, nitrogen gas tankers were used to push a squeegee pig through the pipe with a tag line attached. The pipe was then swabbed dry before pulling vacuum to remove moisture.

C. Cable System Installation

The cable pipes were brought above water on the platforms for cable pulling and, later, splicing. The pipe ends were aligned over an approximately 120m (400ft) long pit in the water bottom. The intent was to provide a location for the cable pipes to lay down after the installation was completed. The work was done from platforms in the water with support from barges; the platforms isolated the tide fluctuations from the exacting work of building the splices. Figure 7 shows one of the work platforms with the pipe ends aligned prior to cable pulling. The pipe was temporarily laid down while divers worked to outline the laydown area. The pipe was then re-raised so that further excavation could be completed in the pits; and then the pipes were lowered into their final resting positions after splicing was completed.

Figure 7: Work platform suspended over water for cable pulling.

Pulling tension calculations were performed for all of the cable runs. Several of the sections were long, and the large-conductor copper cables were heavy (19.7 kg/m, 13.2 lbs/ft) resulting in some tensions that approached but never exceeded the pulling limits (48,000lbs for the 3000kcmil copper cable). Sidewall bearing pressure forces were not an issue because the directionally-drilled sections were generally very straight. The dynamometer on the pulling winch broke for one of the pulls, so tensions could not be monitored effectively.

Figure 8: Cable pulling on one of the long underwater sections.

Installation of the power cables and accessories was a challenge mainly affected by the weather. The Miami area experienced frequent thunder showers that brought sudden and significant quantities of rain causing problems for work in manholes as well as trying to keep the cables dry during pulling, splicing and terminating.

On one occasion, the pulling winch failed during cable pulling for one of the long water sections while thunder showers rolled in. The cable reels were covered with tarps, and the individual phases between the reels and cable pipe were wrapped in plastic to best seal out the moisture. A slow flow of nitrogen gas was pumped through the cable pipe overnight until the winch could be repaired. Despite the challenges presented by the weather, ultimately, all of the cable was pulled into the pipe (see Figure 8).

Building terminations and splices also proved to be challenging due to the weather conditions. Splicing of the cable at the manhole in Miami Beach was difficult because of the weather and the location within the street that happened to lack sufficient drainage during rain storms. On a couple of occasions, the installation contractor had to hurry to close up the manhole before street flooding occurred during sudden thunder showers. For splicing, the contractor fitted the top of the manhole chimney with a section of plastic culvert pipe so that rain runoff in the street would not flood the manhole once cable splicing started. Splicing out in the unprotected areas of the water was facilitated by using a temporary splice shed that was set on top of the platform to provide a controlled environment for cable splicing. Figure 9 shows the temporary splice building setting on one of the platforms.

Figure 9: Temporary work platform for cable splicing on the water.

An additional challenge was getting the pipes to lay down after splicing was completed on the water. This potentially could have been avoided by digging the pits near the splicing platforms deeper.

IV. AS-BUILT AMPACITY CONSIDERATIONS

Ampacity was a critical challenge for the design as the utility had specific ampacity goals in mind. After the installation was complete, an evaluation of the as-built ampacity was performed using Neher/McGrath and IEC 60287 methods [2, 3], including to evaluate the mutual heating effect of other nearby heat-producing cables running in parallel; locations where the new pipe circuit crossed other distributing cables were also evaluated [4]. The Miami end of the cable circuit had good native soil thermal resistivity values (0.8 C°-m/Watt), but the values on Miami Beach were much higher (1.6 C°-m/Watt). The HDD sections were through lime rock. Though the lime rock has a high thermal resistivity when totally dry, it was expected that due to the depth well below the water table and high hydraulic conductivity of the lime rock, the lime rock would remain fully saturated with water even in the presence of heat-producing cables. A "wet" thermal resistivity value of 0.5 C°-m/Watt was used for ampacity calculations; the underwater sections did not limit the overall circuit ampacity.

Low thermal resistivity corrective thermal backfill was used along the open trenched sections of the cable route, and the volume of material installed was increased at crossings on the Miami Beach end of the circuits to mitigate the de-rating effects. Loading levels on pre-existing distribution circuits along with two other pipe-type feeders had to be carefully evaluated. Conservatively, the full capability of each of the circuits was considered initially. However, the utility refined the requirements based on actual circuit loading, and the corresponding heat output from the cables was used to develop the 138kV Overtown-Venetian ratings and considering that coincident peak loading on all the cables would never occur. Though the utility accepted a slight concession on the desired rating, the as-built ampacity met utility requirements.

V. Cable System in Operation

The Overtown - Venetian circuit has proved to be a reliable asset to FPL and provides a valuable 138 kV injection to one of last bastions of 69 kV in the FPL system. It provides operational flexibility and provides relief when other lines go out of service in Miami Beach. FPL is confident that both the cable design and the final route were the optimal choices. FPL constantly strives to be good environmental stewards and feels that the means and methods used to complete this project reflect those efforts. In completing a design that required only two aqueous splices, FPL minimized the impact to Florida's protected sea grasses. Furthermore, because the cable is underground/underwater, it is less susceptible to Florida's frequent inclement weather conditions. The lessons learned here will continue to provide valuable insight into the best means and methods for completing other projects across Florida's pristine bodies of water.

VI. Conclusions

The cable system was successfully energized in September 2009. This project revealed several areas where future projects might benefit, resulting in the following conclusions:

- Project planning and scheduling should consider the amount of time required to obtain all the permits, particularly for projects requiring work in marine environments where the extent of permitting is increased significantly.
- The contractor should consider redundancy of equipment for critical operations like cable pulling (pulling winch, tension monitoring) that could potentially jeopardize the installation of expensive, long-lead time cable.
- A thorough understanding of the implications of other cable circuits and as-built ampacities as compared to actual circuit loading should be carefully evaluated.
- Through coordinated planning, complex directional drilling projects, including where cables must be joined together over water, can be done successfully.
- The project also entailed several project firsts:
  - Joining HDD sections on platforms in the water for the purposes of an electrical cable circuit
  - Installing multiple pipe-type cable segments with separate pulling sections using HDD.
  - Use of a 9-inch cable pipe; the pipe also included a 3/8-in heavy wall for added durability.
  - Use of the 3000kcmil segmental copper conductor size in a HPGF cable system.

VII. Acknowledgments

The work performed during this project encompassed the skills of several people and organizations. Jacobs Civil, Inc. performed the civil engineering design and provided construction management oversight to FPL during the project. UTEC Constructors working with Cashman installed the cable system, with Mears performing the horizontal directional drilling. The Okonite Cable Company manufactured the cable. Maverick manufactured the pipe, and Durabond flared and coated the pipe. MAC Products manufactured the splice kits, and G&W manufactured the terminations. Underground Systems, Inc. manufactured the nitrogen gas cabinet, and CorrPro designed the cathodic protection system that utilized Dairyland's Isolator Surge Protectors. Geotherm, Inc. performed soil thermal testing. The authors prepared the cable system design and supporting calculations, developed cable system related specifications, and oversaw quality assurance during manufacturing, construction, installation and commissioning.

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IX. Biographies

Earle C. (Rusty) Bascom, III (M'1989-SM') holds B.S. and M.E. degrees in Electric Power Engineering from Rensselaer Polytechnic Institute and an M.B.A. from the 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 as a Principal Engineer he continues to provide engineering services in the analysis, design, specification, installation oversight and operational characteristics of underground and submarine transmission and distribution cable systems. He 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 NY, FL and TX. He can be contacted at r.bascom@ec-engineers.com.

Joseph Rezutko (M'2000) holds a B.S. in Electrical Engineering from Purdue University (West Lafayette, IN). After graduating in 2001, Mr. Rezutko worked for Raymond Professional Group in Chicago, IL, before he moved to West Palm Beach, Florida to begin working for FPL in 2003. There he initially worked as a distribution power engineer but has since moved over to the Transmission department. He is currently the High Voltage Underground Transmission Systems engineer at FPL, where he manages all projects related to the underground transmission network. Mr Rezutko is an E.I.T and a member of IEEE, Power & Energy Society and is Vice Chair of the CEATI Transmission Underground Cables Interest Group. He can be contacted at joseph.rezutko@fpl.com.