PJM'S UNDERGROUND & SUBMARINE TRANSMISSION CABLE RATING METHODOLOGY GUIDELINES

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1.0 INTRODUCTION

1.1 Background Information

PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. In the past, PJM has brought together task forces consisting of representatives from the utilities included within the PJM RTO to create ratings documentation, such as the Outdoor Substation Conductor Ratings document from 2010. This documentation allows for the utilities to learn about the processes that their peer utilities use when rating a certain piece of equipment, in this case transmission underground cable and the associated accessories.

The idea of having an Underground & Submarine Transmission Cable Ratings Methodology Guide had been discussed for years but was finally pushed forward by the Heritage MAAC Subcommittee in 2013. The Underground Cable Rating Working Group was established with members from BGE, PECO, PHI, PPL, and PSE&G. This group used their experience and knowledge to create a document to help any utility establish their own practices by explaining the processes and methodologies that they practice at their respective companies. This document should be treated as a ***guide***, providing the reader the different processes, perspectives, and important take-aways that these utilities have experienced and learned from over the years.

1.2 Purpose of Guidelines

The intent of this document is to give guidance to utility companies looking to create or update their existing underground transmission rating methodology. In addition, this document can serve as a tool for new engineers to become familiar with the basics of underground transmission cable ratings. This document describes the fundamental knowledge of ampacity principles, development of transmission ratings, and design and construction considerations. This Underground & Submarine Transmission Cable Rating Methodology Guideline incorporates ratings for voltages 69kV through 345kV for different cable systems including pipe-type cables, self-contained cables, and solid dielectric cables. At this point in time, the participating companies have not installed 500 kV underground transmission lines, however, 500 kV transmission rating methodology generally follows the same principles outlined in this document.

1.3 Ampacity Overview

Ampacity, or current rating of the cable, is the magnitude of the current at a specified voltage that can be transmitted on the cable system without exceeding insulation temperature limits (EPRI, 2006). Cable ampacity is divided into three conditions, normal (steady-state), emergency and load dump, with all ratings impacted by the following factors:

1. Cable Insulation
2. Peak current and load–cycle shape
3. Conductor size, materials, and construction
4. Dielectric losses
5. Mutual heating effect of other heat source like cable or heat source
6. Ambient earth temperature and depth
7. Type of surrounding environment (soil, duct bank, grout) and their thermal characteristics

For more information concerning how cable rating calculations are implemented in the operation of transmission lines, please see PJM Manual 3: Transmission Operations (Section 10.1).

2.0 DEFINITIONS

2.1 Underground Transmission Definitions

1. **Thermal Resistivity** is a heat transfer property used to evaluate current soil conditions and to grade thermal backfill in underground transmission line construction. This property is a measurement of a temperature difference by which a material resists heat flow.
2. **Pipe-Type Cables**, also known as High Pressure Fluid Filled (HPFF), have three phases insulated with tapes of kraft paper or laminated paper polypropylene (LPP) installed in a steel pipe pressurized with dielectric fluid. High Pressure Gas Filled (HPGF) cables have three phases insulated with tapes of kraft paper or laminated paper polypropylene installed in a steel pipe pressurized with nitrogen.

3. **Self-Contained Cables**, also known as Self-Contained Fluid Filled Cables (SCFF), up to three phases, each phase consisting of a hollow core conductor, paper insulation, a lead or metallic sheath, and a protective outer jacket. The hollow core conductor may be wrapped around a steel tube that houses a low viscosity dielectric fluid.
4. **Solid Dielectric Cables** is a type of cable where the insulation material is extruded over the conductor shield and then cross-linked for cross-linked polyethylene or ethylene-propylene rubber. Three types of solid dielectric cable are XLPE (Cross-linked Polyethylene), EPR (Cross-linked Ethylene Propylene Rubber), and PE (Thermoplastic Polyethylene).
5. **Load Factor** is the ratio of the average loading to the peak loading over a 24 hour period.
6. **Loss Factor** is the ratio of the square of the maximum hourly reading to the sum of squares of the hourly current ratings over a 24 hour period.
7. **Conductor Maximum Temperature** is defined by industry standards that are based on damage limits for the insulating material adjacent to cable conductor. There are industry allowances to vary the temperature limits when select design parameters are not well known (EPRI, 2006).
8. **Ambient Earth Temperature** is the temperature of the native soil that may change seasonally.
9. **Adjacent Heat Sources** are any localized heat sources including steam pipes, distribution circuits, and transmission circuits that impact ratings due to mutual heating.
10. **Grounding** of transmission cables maintains a continuous ground path to permit fault-current return and lightning and switching surge protection (EPRI, 2006).
11. **Route Thermal Analysis** is based on a field survey used to gain an understanding of the environment surrounding the selected path of the cable at the expected system depth.

12. A **fault** is a physical condition that results in the failure of a component or facility of the transmission system to transmit electrical power in a manner for which it was designed (PJM Manual 35, 2015).
13. **Fault Current Capability** is the maximum allowable current that a cable can withstand during a fault.
14. **Ampacity Software**
    a. **CYMCAP©** is Windows-based software designed to perform thermal analyses. It addresses both steady state and transient thermal cable ratings. These thermal analyses pertain to temperature rise and/or ampacity calculations using the analytical techniques described by Neher-McGrath's paper for cable ratings and IEC 853 International standard (Section 10.1).
    b. **Underground Transmission Workstation©** is an EPRI software product based on standards and techniques including IEC 60287 and Neher-McGrath's paper for cable ratings (Section 10.1).

3.0 CABLE COMPONENTS

There are three major cable system types utilized in underground transmission and submarine circuits, which include pipe-type cable, self-contained fluid filled cable, and solid dielectric cable.

3.1 Pipe Type Cable

Pipe-type cables have three cable phases insulated with tapes of kraft paper or laminated paper polypropylene (LPP) and are installed in a common steel pipe. This cable system is pressurized with dielectric fluid (referred to as High Pressure Fluid Filled) or nitrogen (referred to as High Pressure Gas-Filled). Armored cable is an option for a pipe-type cable system, where a long lay "flat strap" stainless steel armored wire is applied directly under the skid wires.

The **conductor** material should be soft drawn copper wire or half hard aluminum wire before stranding. The stranding configuration shall be compact round or compact segmental made of four segments and bound together with binder tape. Copper conductors are utilized for maximum power transfer.

The **conductor shielding** has a minimum of two semi-conducting carbon–black tapes wound in a smooth and tight manner. The conductor shielding is then taped, which provides a uniform transition from the conductor shield to the insulation. Shielding reduces electromagnetic interference.

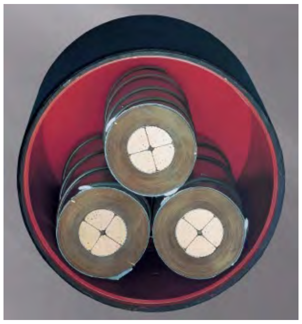

Figure 1- Pipe-Type Cable (Retrieved from Zimnoch's ICC Presentation)

The **insulation material** consists of the best quality kraft paper or laminated polypropylene paper (LPP), which is also known as paper-polypropylene-paper (PPP). Insulation helps to protect the shielding and allows the shielding to work properly (EPRI, 2006).

The **insulation shielding** has a minimum of two metalized tapes for transmission cables. This shielding is very similar to the conductor shielding, but varies in design based on the voltage class and dissipation-factor requirements.

The **outer cable shielding** shall have one stainless steel intercalated with one plain Mylar/ polyester tape. The purpose of the outer shielding includes metallic drainage of capacitive charging current, adequate short-circuit current-carrying capability, protection against external mechanical damage, protection from moisture ingress into the cable, reduction of impregnant drainage during shipment and storage, mechanical strength during and after insulation, and pressurizing enclosure (EPRI, 2006).

The **skid wires** (two) shall be D shaped (0.100”x0.002”) and are applied with three inch lay. The skid wire material can be stainless steel, zinc, and brass. The purpose of the skid wire is to protect the outer shielding assembly and reduce the coefficient of friction between the cable and pipe during installation (EPRI, 2006).

3.2 Self-Contained Cable

Hollow core, or self-contained, cable designs are one of the early medium-high voltage cable systems to be made available to the utility industry. These cable systems are either single or three core conductor cables. Single core conductor cables have a hollow core conductor that contains a steel tube which houses a low viscosity dielectric fluid. The three core conductor cables contain solid conductors with steels tubes bundled into the cable alongside the conductors. This self-contained setup allows the insulation to be pressurized internally.

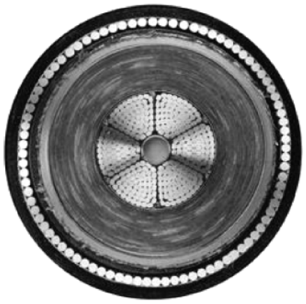

Figure 2- Self Contained Cable (EPRI, 2006)

The cable design may include a **center duct** with a steel spiral tube that allows the fluid to pass through and impregnate the insulation.

The **conductor** is stranded from copper or aluminum wires. Three-core cables are stranded from circular wires where as single core cables include a central fluid duct (EPRI, 2006).

The **conductor shield** is a semi-conductive layer that encloses the conductor via a series of carbon black tapes.

The **paper insulation** consists of either oil impregnated kraft paper or laminated paper-polypropylene. Impregnated paper insulation is used for this cable system and is one of the most common insulating materials used for transmission cables.

The **insulation shield** is a series of carbon or metalized carbon paper tapes. The shield provides a conducting grounded electrode around the insulation.
The **lead or metallic sheath** is generally a lead alloy or a corrugated aluminum. The sheath provides containment of the cable and fluid and also serves as a path for fault current.
The **outer jacket** is a final polypropylene protective layer.

The cable system is pressurized by tanks that are located within the substation or a manhole. The internal pressurization of self-contained cable is generally achieved through a series of gravity fed tanks. The head pressure from the tanks is what is seen by the cable (approximately 2-10 psi). Another feature required of SCFF systems are reservoir tanks. A reservoir tank is a bladder that expands to take on fluid from the cable during the heating cycle and contracts to release fluid back into the cable during cooling

Medium Pressure Fluid Filled (MPFF) cables

Medium Pressure Fluid Filled (MPFF) cables are newer designs of the self-contained fluid filled systems. They are constructed with paper insulation and aluminum or reinforced lead sheaths and commonly operate at 75 psi. Several utilities consider any nominal operating pressure below 100 psi to be medium pressure.

Low Pressure Fluid Filled (LPFF) cables

Low Pressure Fluid Filled (LPFF) cables were generally pressurized to 5-15 psi. Various utilities have different views on what classifies low pressure versus medium pressure. The most commonly accepted differentiation is gravity fed verses a pumping system. Low pressure cables are most commonly referred to on systems that utilize the gravity fed tanks.

3.3 Solid Dielectric Cable

Extruded-dielectric cable systems work the same as fluid filled systems, the main difference is the absence of the dielectric fluid in the extruded-dielectric systems, allowing for simpler accessories and maintenance practices. Extruded-dielectric, or solid dielectric cables, utilize crosslinked polyethylene (XLPE) or ethylene-propylene rubber (EPR) insulation. XLPE cables are characterized by small dielectric losses relative to paper, LPP, and EPR cables, allowing for ampacity capacity increases at transmission voltages. Solid dielectric cables have similar components, with the insulation being the main difference.

The **conductor** is stranded copper or aluminum. For sizes larger than 1250kcmil the conductor is segmented to reduce the ac/dc resistance ratio. For very large conductor sizes, manufacturers coat each strand with enamel or cupric oxide.

Figure 3- Solid Dielectric Cable (provided by PPL)

The **semiconducting tape** is bedding tape that is wrapped around the conductor before being placed in the extruder, blocking little pieces of the conductor shield from getting in between conductor strands.

The **conductor shield** is used as a smooth interface between the conductor and the insulation, and forms a uniform electric field.

The **insulation** varies between the different solid dielectric cable types and is added to the cable by extrusion.

The **insulation shield** is similar to the conductor shield because it creates a uniform electric field. The conductor shield, insulation, and insulation shield are often extruded together in the manufacturing process.

NOTE: The following material layers described are not consistent throughout cable designs and will vary between manufacturer (material and order in cable layers), excluding the jacket which all solid dielectric cables have.

A **metallic shield** carries the charging current and fault current that may occur. It consists of copper wires, copper tapes, or a combination of the two.

A **water-impervious sheath** is made of lead, corrugated aluminum, or metal foil applied over the metallic shield. When lead or aluminum sheaths are used, they become part of the metallic shielding.

A **bedding/water blocking layer** is the semiconducting layer that usually resides between the insulation system and the metallic shield/sheath. It protects the insulation from deformation due to thermal radial expansion of the core and lateral pressure at bends at maximum normal and emergency operating temperatures.

NOTE: An additional layer of water swelling tape or powder is applied in some cables, to prevent longitudinal water penetration (after the insulation shield and before the jacket).

The **jacket**, made of PVC or polyethylene, is used to prevent corrosion of lead or aluminum. If no metallic sheath is used, it protects the cable during handling/installation and prevents moisture penetration.

3.4 Cable Accessories

Ratings of cable accessories should always be designed to meet or exceed the cable rating.

Terminations

The basic function of a termination is to allow for the transition from underground cable to substation bus. Terminations, also known as potheads, house a single conductor and a stress control mechanism in a sealed housing. Terminations of solid dielectric cable systems are either dry, filled with dielectric fluid, or filled with a silicone-based fluid, while terminations of fluid filled systems are filled with the same dielectric fluid that is within the pipe or cable. Termination failures can occur due to a number of reasons, such as cracking of different components inside the insulator (gaskets, stress cone, etc.) which would cause the fluid inside the housing to leak out and empty, outside influences (bullets, trees, etc.) and cable creepage (the cable slips or is pulled down out of the termination).

Figure 4– HPFF Termination (provided by PECO)

Splices/Joints

“The basic function of a splice is to join cable sections in a confined space. To fulfill its purpose a splice must provide a robust conductor connection surrounded by an adequate dielectric system within a suitable grounding enclosure or covering” (EPRI, 2006).

Cable movement occurs after numerous loading cycles due to traffic vibrations, circuit path elevation, and loading. The cable moves with the heating and cooling of the system. Many failures occur when the cable has moved so much that it has jammed itself in one of the joint ends and can no longer move.

Figure 5- HPFF Repair Splice (provided by BGE)

Manholes

Manholes are usually permanently installed at locations where cable pulling and splicing are necessary. These manholes also provide access to sample ports or valves for dissolved gas analysis sampling. Splices are usually created inside manholes, to allow for maintenance or repair if a fault does occur. In self-contained systems, there can also be alarming equipment located within the manhole.

Link boxes

Link boxes are designed to provide easy access to the sheath bonding. The access allows for inspection and removal of grounds from the sheath bonding connections, to permit integrity testing of the cable's insulating jacket. "At locations where overvoltage protection of shield/sheath interruptions is provided, the link box contains the surge diverters physically and electrically close to the points to be protected" (EPRI, 2006).

Figure 6- Link Box (provided by PECO)

Anchoring Systems

"Anchor and skid joints are used with armored cable when cable is installed on a very steep incline or in long vertical risers. The anchor joint is installed on the top and supports most of the weight of the cable. The skid joint is installed at the bottom of the incline or riser and permits the cable to expand and contract with load changes" (EPRI, 2006).

Pumping Plants

Pumping or pressurizing plants maintain the insulation integrity of pipe-type cable systems. Fluctuation of oil volume with temperature requires the use of a pumping plant to maintain hydraulic stability, while maintaining the appropriate dielectric insulation around the cables in the pipe.

Figure 7- Pumping Plant (provided by BGE)

Heat Exchangers

Heat exchangers are implemented in HPFF systems to air cool dielectric fluid and dissipate heat to the environment. Fluid is routed through a series of tubes that are air cooled using fans and natural convection. Heat exchangers are often used in conjunction with refrigeration cooling units.

Figure 8 - Heat Exchanger (EPRI, 2006)

4.0 CABLE ENVIRONMENT

4.1 Soil Properties & Direct Buried Cable

Soil is a composite material consisting or solid particles, water and air. Heat flows through soil from particle to particle.

Thermal resistivity (or “rho”) is a material characteristic that relates the extent of temperature rise caused by 1 Watt per square meter passing through 1 cubic meter of the material. Thermal resistivity is used to characterize how the temperature will change as heat moves through a material such as the soil around the power cables.

Factors that affect soil thermal resistivity:

1. Soil composition - mineral type and content, organic content, and chemical bonding between particles
2. Texture - grain size distribution and grain shape
3. Water content - degree of saturation
4. Dry density – porosity, solids content, inter-particle contacts, and pore size distribution
5. Others - solutes (dissolved salts and minerals) and loss of fines (leaching)

In the case that the native soil is very poor, methods of controlling thermal resistivity are introduced. It is generally not feasible to modify the thermal resistivity of the native soil, so selecting materials with a good thermal resistivity and stability to backfill a trench are used to offset the negative effects of the native soil. A common material used is Controlled Backfill, also known as Thermal Sand, which is made of well-graded sands and crushed stone. The controlled backfill should be compacted in the trench to reach a desirable thermal resistivity. Another option to improve the thermal performance of the external thermal environment is an imported material commonly referred to as Fluidized Thermal Backfill (FTB). FTB is a concrete-like mixture of natural aggregate, water, sand, cement that includes a fluidizer, such as flyash, developed to meet thermal needs (EPRI, 2006). The thermal characteristic of this concrete-like material will result in an overall lower thermal resistivity, typically between 50-70 ◦C-cm/W (EPRI, 2006). Utilities have used both high strength and low strength FTB depending upon project circumstances. Generally, a geotechnical expert is consulted to work with local suppliers in developing a mix design for FTB. In casings or special applications, a thermal grout can be used to lower the thermal resistivity of traditional grout. This new thermal resistivity, as known as “effective resistivity”, is used in the ampacity calculations.

4.2 Pipe

Pipe-type cable systems consist of three paper-insulated cables, one per phase, which are installed in steel pipe. This type of cable system is still being installed to this day, mostly in urban areas, due to the known reliability of the system and the small footprint of the steel pipe in comparison with the footprint of solid dielectric duct banks.

The pipe size depends on the size of the pipe-type cable that will be installed. Listed below are some of the common sizes for steel pipes used in pipe-type systems as well as their typical voltage class.

Figure 9 - Typical Pipe Sizes

Typical Pipe Size (nominal ID)	Typical Pipe Size (outer diameter)	Typical Voltage Class
6”	6.625”	69 kV -138 kV
8”	8.625”	115 kV – 230 kV
10”	10.75”	230 kV – 345 kV

The typical types of pipe filling mediums used in cables in the United States are alkylbenzenes, polybutenes, and mineral oils. Alkylbenzene liquid and mineral oil have been blended to reduce the likelihood of forming gas under voltage stress and with polybutenes liquid to reduce viscosity. Alkylbenzene, polybutene, and blends of both are used as components in HPFF cables.

HPGF systems generally use ASTM Type III dry nitrogen. The dry nitrogen is usually delivered to the site by a tanker in liquid state, and then a heat exchanger is used to convert the nitrogen from liquid state to a gas state before being installed in the pipe.

Four basic types of pipe coatings that have been successfully used on pipe-type cables include asphalt mastic, coal-tar enamel, polyethylene, and polypropylene. Steel pipe was originally thickly coated with Somastic (asphalt mastic) or coal-tar enamel. Please be aware that Somastic coatings may contain asbestos, so proper safety protocol must be adhered to when working under these conditions. Polyethylene and polypropylene coatings are most commonly used today. Thin film or fusion-bonded epoxy coatings have not been used for pipe-type cables because of their low electrical strength.

The values listed below are for polyethylene and polypropylene pipe coatings. The required resistance in ohms for any length of pipe installed is determined by dividing the minimum coating resistance listed in ohms per 1000 feet of pipe length by the total length of pipe under test in thousands of feet (EPRI, 2006).

Figure 10 - Table of Minimum Coating Resistance (EPRI, 2006)

Typical Pipe Size (nominal ID)	Surface Area Sq. Ft. Per 1000 Ft Pipe	Minimum Coating Resistance in Ohms Per 1000-Ft Pipe Length
6”	1740	5750
8”	2260	4500
10”	2820	3600

Corrosion of the steel pipe can occur due to a chemical reaction with its environment after the steel has been buried for an extended period of time. This chemical reaction occurs because electrons from the steel are discharged into the soil and join with the hydrogen ions to form hydrogen gas. It is not uncommon for rust to form on the surface of the pipe, which can cause the steel to corrode away.

Cathodic Protection is a means to guard the steel pipe from corrosion. Cathodic protection requires dc current to be applied to the steel pipe by either a galvanic or impressed current anode and by maximizing the pipe to ground resistance by the use of dielectric coatings and isolation from other grounded structures. Pipe-type cables have to be connected to substation ground mats for ac fault current protection. Since pipe-type cables have to be electrically continuous to allow fault currents to travel, the cathodic protection must be applied along the entire pipe length and cannot be isolated into sections.

4.3 Duct

Unlike HPFF cables that are installed in steel pipes, self-contained and solid dielectric cables are installed in either duct or are directly buried into the surrounding medium. Directly burying cable will allow for a higher rating available, due to the lack of air around the cables (dead air space impedes heat transfer). “Duct banks are defined as a group of ducts installed in the same trench in an orderly layout design” (EPRI, 2006). Duct banks are used to protect the cable from dig-ins and allow for a less problematic process for cable replacement. The duct bank, if not damaged, allows the cable to be pulled (removal of damaged cable and installation of new cable) through the conduits, eliminating a majority of the excavation needed for cable replacement on a direct buried cable.

Ducts are installed in either a vertical or horizontal arrangement, depending on obstructions in the designed cable path, ratings limitations (the deeper the cable is or the deeper the duct the cable is installed in, the lower the cable ratings will be), or utility configuration preference. Spacers hold the ducts in place until the concrete is poured. The concrete disperses and creates an enclosure around the ducts, cementing them in place.

The configuration of the cable within duct bank is critical when calculating cable ratings. The configuration of the duct bank can also impact the mutual heating between circuits in the duct bank. The configuration and arrangement depend on the number of circuits and cables being installed in the duct bank and any adjacent heat sources located near the duct bank. In these cases, the cable might be spread out more inside the duct bank or the cables might be arranged on the opposite side of the adjacent heat source to minimize mutual heating affects.

The primary duct materials used currently is PVC (polyvinylchloride), PE (polyethylene), and fiberglass (reinforced thermosetting resin). Ratings may vary depending on the conduit material and thickness used. These materials have a lower coefficient of friction, allowing for longer lengths of cable to be pulled through the duct. “Some utilities use heavy-wall ducts even when they will be encased in concrete because during the curing process, thin-wall ducts have sometimes deformed and become more of an oval shape” (EPRI, 2006). This may slow down or hinder the cable pulling process, or damage the cable being pulled into the ducts.

5.0 TRANSMISSION RATINGS

5.1 Normal, Emergency, & Load Dump Ratings

Normal Ratings

This is the ampacity that represents the continuous, steady state load that the cable can carry based on a given design. Operating the cable system at or below this level will not result in any degradation of the cable insulation or shorten the nominal life of the cable system.

Emergency Ratings

While normal ratings have no limiting application time period, various emergency situations permit higher current-carrying capacity for a finite period of time during which accelerated aging may occur. Some utilities choose to differentiate ratings between a short duration (“short term emergency” or “STE”) and a long duration (“long term emergency” or “LTE”), however, these ratings are set equal for PJM use unless specifically approved otherwise (See PJM Manual 3: Transmission Operations for more information). In situations where there are two circuits in a common trench, some utilities choose to differentiate the emergency rating(s) to include situations where one of the two circuits is out of service (e.g., “one out” emergency). The emergency rating will be impacted by the preloading condition of the cable.

Load Dump Ratings

Load Dump ratings are used by system operators during a brief duration emergency situations to relieve the system without causing permanent damage to the transmission assets. If the loading exceeds the emergency rating but remains under the load dump rating, the system operator has 15 minutes to relieve the overload. If the loading exceeds the load dump rating, the system operator has 5 minutes to relieve the overload below the emergency rating including, if necessary, by shedding load (PJM Manual 3, 2015).

5.2 Cool Down Times

The temperatures applied to normal and emergency ratings are based on industry standards and utility practices. Once a circuit has experienced loading above the normal rating, its loading must be reduced to or below its normal rating for a period of time, at the utility’s discretion, before applying an additional emergency. If another emergency loading condition is applied too soon, the cable and surrounding soil will not have cooled down adequately to avoid the peak temperature exceeding the emergency temperature limits. This is effectively a “cascading” of emergencies that can damage the cable.

5.3 Cable Operating Temperatures & Rating Durations

The table below displays a range of typical cable operating temperatures accepted by various utilities within PJM's territory for normal and emergency ratings. This table also includes the allowable durations that are used to define emergency ratings. Please note that the load dump duration is mandated by PJM's Transmission Operations Manual 03.

Figure 11 -Various Utilities' Cable Operating Temperatures & Rating Durations

Conductor Temperature & Rating Durations	**Typical Values**
Normal (°C)	**Normal (°C)**
XLPE	90
EPR	90
HPFF (Static)	75-85
HPFF (Oscillation & Circulation)	80
Self-contained	85
Emergency (°C)	**Emergency (°C)**
XLPE	105
EPR	105 - 130*
HPFF (Static)	95-105
HPFF (Oscillation & Circulation)	100
Self-contained	100 - 105
Emergency Allowable Duration	**Emergency Allowable Duration**
Emergency (hours)	0.5 - 300 hours
Load Dump Duration	**Load Dump Duration**
Load Dump (minutes)	15 minutes [10.5]

Notes:

(a) The historic cable operating temperature for solid dielectric cable emergency rating of 130 (°C)

5.4 Defined Seasons & the Seasonal Effects on Ratings

Traditionally, utilities have defined winter and summer seasons depending on their region. The summer season usually ranges from late spring to early fall and the winter season usually ranges from late fall to early spring. It is important to note that underground and submarine transmission ratings are affected by seasonal changes in soil temperature rather than air temperature. The seasonal affects may be occurring after the traditional season ranges because of the depth of the underground or submarine transmission cable. Periodical reviews of load patterns are needed to be sure that loss factors used in calculations are representative of actual seasonal conditions. Appropriate adjustments should be made to rating calculations using a representative value of daily loss factor.

6.0 DESIGN CONSIDERATIONS

6.1 Depths to Use for Ratings

Determining burial depth should be based on heat transfer and the thermal resistivity of the surrounding soil. All heat generated by the cable must eventually reach the surface. As cables heat up, they must dissipate the heat and the effectiveness to do so is based upon the distance to the surface as well as the composition of the surrounding environment. The surface of the earth is most affected by the ambient temperature and follows seasonal changes at shallower depths. Assuming no atypical influences, it is generally more beneficial to have shallower burial depths. Traditional burial depth for pipe-type cable is 36 – 42 inches (approximately 91cm – 107 cm) below grade to the center of the pipe. However there are several factors that may require you to adjust this rule of thumb. Actual field conditions will often dictate exactly where you are able to install a new cable system. Ground obstructions, moisture content, nearby heat sources, and/or surrounding soil are all components that may make it more desirable to set the true burial depth deeper or shallower.

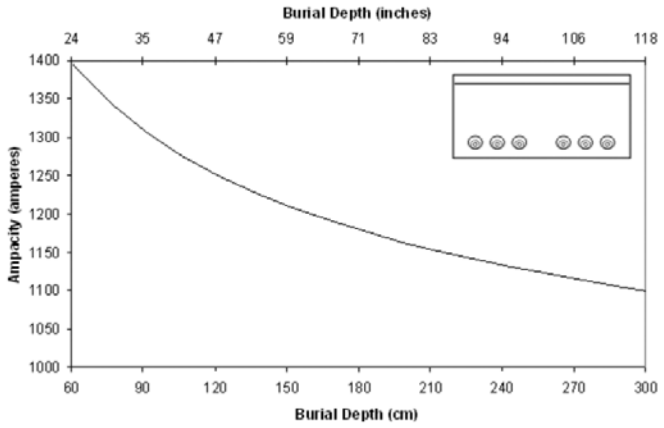

Figure 12 - Effect of Burial Depth on Ampacity (EPRI, 2006)

6.2 Abnormal Lengths of Burial

After the cable path has been designed by the utility, the utility analyzes the transmission line drawings to determine the different depths of burial for each cable configuration (direct buried, duct, etc.). Some utilities choose not to model different cable configurations unless it has reached a certain distance in length (typically 50 feet) due to assumed axial cooling in the cables that would have minimal effects on the ampacity. Utilities have different views on when to model minor changes of lines of shorter lengths of burial, so it is generally left to the utilities' discretion.

6.3 Soil Ambient Temperatures

Heat produced by underground transmission cables flow into the ambient earth, so when performing ampacity calculations we have to consider the ambient soil temperature. There is little control over the ambient soil temperature; however, an important factor to consider is the burial depth for the cable. The closer the cable is to the surface, the more fluctuation in the ambient soil temperature in extreme temperature changes. For example, the soil ambient temperature can vary ten feet below the surface depending on the time of year. The soil covering can also have an impact of the ambient soil temperature.

6.4 Adjacent Heat Sources

Adjacent heat sources pose issues to cable ratings due to the mutual heating between the transmission cable and these additional heat sources. These adjacent heat sources, such as steam lines, distribution cables, or transmission cables, may cause significant de-rating of the transmission cable that is being rated.

Steam lines are a high heat source. Depending on the proximity of the steam line, the engineer will try and design the cable system line to be outside the zone of influence of the steam line to mitigate this problem. Steam lines not only pose a problem in terms or cable ratings, but also with potential risk of a leak affecting the environment near the transmission cables.

The engineer needs to model the distribution cable(s) in the zone of influence in the transmission cable ratings analysis to determine what impacts it will have to the overall cable rating for the system. Some possible solutions for distribution line crossings/adjacent distribution cable heat sources are listed below:

- Relocate the distribution lines to remove them from the zone of influence.
- Increase the conductor size of the distribution lines at the crossing.
- Increase the FTB area or choose a different backfill so that the backfill thermal properties are optimal for heat removal.
- Select a different route/cable path.
- Install a Forced Cooling system.

The same rules apply to adjacent transmission cables as they do with adjacent distribution cables, but there is less flexibility for adjacent transmission cables. During the line design process careful attention needs to be given to these crossings. Increasing transmission cable size or relocating other transmission lines is an expensive process and if required, this work should be included in the new line construction work. The prudent design approach is to place the new line outside the zone of influence, to avoid mutual heating.

If it is not possible to avoid the adjacent heat sources, then the mutual heating affects will need to be included in the ratings analysis of the transmission cable. For adjacent distribution and transmission cables, the mutual heating from this newly installed transmission cable will also need to be considered and factored into those adjacent heat sources ratings, since they may need to be derated as well. EPRI determines that “the presence of other heat sources within a distance of about 12ft will reduce the ampacity of a cable system” (EPRI, 2006).

6.5 Hot Spot Mitigation

Hot Spots are sections of the transmission cable that may experience above normal temperatures due to a variety of different situations driven by the cable’s environment. These situations include but are not limited to the following:

- Direct buried circuits with short sections of cable in conduit
- Locations where underground cables transition to overhead lines (terminations)
- Cable installations with sections of high native thermal resistivity soil
- Areas where soil is thermally unstable
- Areas where cable route passes near external heat sources

Utilities must conduct field study to identify the source of any hot spot. The following list includes suggestions and solutions that may help mitigate some well-known hot spot sources without derating the circuit:

- Selecting a larger cable can be used to meet ampacity needs.
- Installing thermal backfill can mitigate thermal issues with native soil. Most backfills consists of uniformly graded granular materials with a weak binder to assure good thermal contact between grains and eliminate the possibility of moisture movement in the backfill.
- Using a forced cooling system in which chilled water circulates through pipes placed near the cables. Cable and water temperatures must be continuously monitored. Forced cooling is economically feasible for only short segments where cables are routed through a thermal bottleneck (a steam line or other heat sources)

6.6 Vegetation

When designing a transmission circuit path, an engineer must remember to not only be aware of other utilities (gas mains, water mains, etc.) located within that portion of the right-of-way, but also take into consideration the problem that vegetation can pose to the underground transmission system. Two areas of concern in relation to vegetation are damage to the cable system by the vegetation root systems and the water within surrounding soil. Due to the depth of burial for most underground cable systems, these two concerns could possibly affect the physical integrity and ratings integrity of the underground cable.

Vegetation Root Systems

Vegetation root systems can span far around the plant/tree and can weave a tight network in the surrounding area. Root systems could travel through the soil and eventually come into contact with the cable or pipe. The cathodic protection equipment could become compromised if the root system interferes with the pipe coating, causing the steel pipes to corrode over time.

When designing any new system and when maintaining in-service systems, be aware of the environment surrounding the cable path. Monitor any vegetation that is growing near the cable path and cathodic protection boxes due to the potential risk of damage.

Water Influence

Vegetation systems pull the moisture out from the surrounding soil so that the vegetation can continue to grow and reproduce. The soil surrounding the vegetation could become dry over time due to an inadequate water supply. This change in soil over time could affect the cable rating calculations. The drier the soil, the less moisture is included, the more resistant the soil becomes.

For new installations, it is a good idea to have soil samples completed before the system is installed, to establish a soil resistivity to use in the initial cable ratings calculations. Be conservative and use the most limiting soil resistivity in the calculations, to allow for any changes in the soil over time. It is recommended to sample the soil periodically if the environment changes near the cable system.

7.0 SPECIAL APPLICATIONS

7.1 Exposed Cables/Pipes

When calculating the ratings capacity of an underground transmission cable, the worst scenarios are modeled (biggest depth, river crossing, etc.). Most utilities model the cable entering the termination, where the cable is exposed to the air, especially if the cables are on a riser structure.

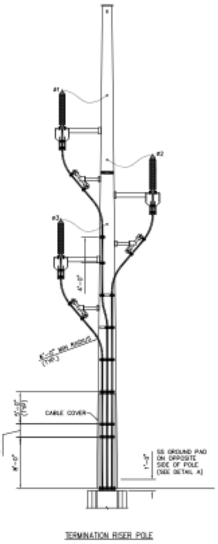

Figure 13- Riser Pole Drawing (provided by BGE)

According to EPRI, the principal differences for in-air cables are:

- Solar radiation provides input heat. Please note the Neher-McGrath calculation does not consider this heat input.
- Heat transfer by conduction is negligible (unlike for buried cables).
- Heat transfer for cables in air is by forced convection or radiation.

The ampacity of an otherwise identical cable circuit will be greater when installed in air than installed in the ground (EPRI, 2006).

7.2 Rating Improvement

Dynamic Line Rating – Fiber Optic Cable in Cable and DTS system

Utilities use Dynamic Line Rating (DLR) to increase the real-time rating of their pipe-type cable circuits. The DLR calculates a rating based on the circuit current conditions that exist in real-time. Temperature sensors and current transformers are strategically placed along the cable pipe to monitor the temperature and loading condition software will calculate the rating based on the actual data.

In pipe-type cable systems, fiber optic cable cannot be embedded in the cable because of the high pressure environment in the pipe. In extruded cable systems, the fiber can be embedded into the cable layers during the manufacturing process. This makes power cable splicing more complicated. Many utilities choose to run fiber in smaller PVC conduit closer the cable.

With this system, ratings are not consistent and change from day to day. The nature of ratings prior to the DTS or DLR systems is that they are static; values are plugged into an equation then a rating is obtained for a pre-defined set of conditions. Below are reasons why these ratings would change daily:

- Load and loss factors are computed real-time based on historical data recorded in the DTS rating program. Depending upon the line’s load cycle these values can change with regularity, while in the static version these values do not change.
- Emergency ratings values are influenced by a preload value. In the static calculations these preload values are assumed. In the real-time rating system, these values are calculated based on real-time data that is stored in the ratings program.

Forced Cooling

Forced cooling systems are applicable to fluid filled cable systems with the goal to maximize ampacity while minimizing size. In traditional HPFF systems, the fluid within the transmission pipe is pressurized to a nominal 200 psi and remains static. In forced cooling systems, the fluid must still remain pressurized to achieve the desired dielectric properties but it does not need to remain static.

Forced cooling systems incorporate two major attributes; circulation and cooling. The circulation is achieved by creating a loop. The loop consists of a pumps and a return path. The cooling is achieved via the heat exchanger which is installed in series of the coolant loop.

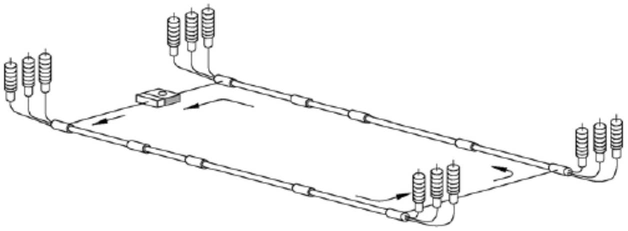

Figure 14- Forced Cooling Loop (EPRI, 2006)

8.0CONSTRUCTION CONSIDERATIONS

8.1 Unique Duct Design

In unique circumstances, a non-standard duct bank design must be utilized to accommodate environmental obstacles that are present in the cable path. One way to determine ratings for a unique duct design is to use fiber and thermocouples to determine what the cables would experience in the configuration. Another way of determining this is, if this design configuration is done before the cable is purchased for the project, certain cable manufacturers can install fiber in the cable, which can be utilized to get a "real-time" indication of the ratings capacity/heating experienced.

8.2 Submarine Cable for Water Crossing Installation

The core of a submarine cable is essentially the same as pipe-type cable, SCFF (Self-Contained Fluid Filled) and extruded-dielectric land-based cables. The major difference is submarine cables are designed to be either coiled or wound onto a turntable to permit very long splice-free lengths and be installed at significant water depths. Many utilities also chose armored cables for added protection during installation and service. Pipe-type submarine cables would require splices approximately every mile including the water sections and are limited to shorter lines for practical reasons. Generally, EPR-insulated cables are employed for lower ratings submarine cable lines with lengths less than a mile.

The most common method of providing protection against mechanical damage in service is by burial in the seabed. The phases spaced at distances equal or greater than the water depth to provide a sufficient space for a U-shaped laying configuration that may be necessary to repair the mid cable without overlapping the other cables. In these conditions, the induced circulating currents in the metallic sheath and armor are practically the same as the current circulating in the conductor.

Another very important mechanical aspect that should be taken into consideration during the mechanical design of submarine cable is to avoid the hydrostatic pressure collapse during or after installation at high depths. At present, there are no U.S. test standards or recommendations for submarine cables. The only relevant U.S. document on this subject is an IEEE guide to submarine power cables (IEEE 1120, 2004).

8.3 Trenchless Installation Methods

Jack & Bore

Jack and Bore, also known as auger boring, is a method of trenchless underground cable installation. This practice involves augering holes and jacking a casing into the hole at the same time. As the casing is being jacked into the ground, soil in the encasement is being removed by a rotating auger. This installation technique is often used to provide a straight pathway for underground cable systems under railroad crossings, roadway crossings, and major intersections. Jack and Bore is a less costly method of trenchless installation, however, the route created with the Jack and Bore method can only be a straight path and less than 400 feet.

Horizontal Directional Drilling

Horizontal Direction Drilling (HDD) began as a trenchless installation method for utility distribution lines, and eventually, larger machinery was developed for utility transmission lines. Originally, HDD was only considered as an alternative for transmission lines when there was a major waterway crossing because of the long distance that the drill could travel. Currently, HDD is at least considered for most transmission projects when open-cut trenching is not an option.

HDD has many positive factors when compared with the jack and bore method of trenchless installation. HDD allows for reasonable curves whereas the Jack and Bore method requires a straight route. The HDD also allows for longer drilling distances with a lower environmental impact. The most significant drawbacks to the HDD method are the high cost of the drilling equipment and the deep cable burial depth that negatively affects the ampacity of the cable.

Microtunneling

Microtunneling is a digging technique used to construct small tunnels. These small diameter tunnels make it impossible to have an operator in the machine itself. Instead, the microtunnel boring machine (MTBM) must be operated remotely. Microtunnel boring machines are very similar to tunnel boring machines (TBM) but on a smaller scale. These machines generally vary from 2 ft. 0 in to 4 ft. 11 in (0.61 to 1.5 meters). Usually the operator controls the machine from a control room on the surface of the ground. In most microtunneling operations, the machine is launched through an entry eye and pipes are pushed behind the machine. This is a process often called pipe jacking and is repeated until the microtunneling machine reaches the reception shaft. Generally, microtunneling is only used when Jack and Bore and HDD methods are not in option because the casing diameter is too large (greater than 3.5 feet) or where a significant amount of rock is encountered. Microtunneling is much more expensive than the other trenchless methods, so it is only used when the other methods are not feasible.

9.0 RATING CALCULATION INFORMATION

9.1 Published Ratings Values

It is recommended that transmission engineering follow the necessary procedures to determine the actual rating with the goal of meeting the desired rating provided by planning. Durations of emergency ratings are determined at utility discretion for operation needs and asset management. It is desirable to have cable ratings calculated during the transmission design phase as well as after the project has been completed based on information provided by the as-built drawings.

A routine effort must be made to verify modeled ratings through data collected during maintenance activities. It is recommended to rerate cables when there are known changes to the circuit's surrounding environment, such as changes to adjacent distribution duct banks. It is also recommended that cable ampacity ratings are re-run and updated upon notice of any version updates for any ampacity software.

9.2 Various Input Parameters

The table below includes a range of typical values used by various utilities within PJM's territory for ampacity calculations. Please see the most recent edition of the EPRI Underground Transmission Systems Reference Book for the current industry recommended values.

Figure 15 - Various Input Parameters

Input Parameters	Typical Range of Values
Ambient Temperature (°C)	Ambient Temperature (°C)
Summer	20 - 35
Winter	10 - 20
Backfill Thermal Resistivity (°C-m/W)	Backfill Thermal Resistivity (°C-m/W)
Native Soil/Sand	0.9 - 1.2
Concrete	0.6 - 0.85
Granular Thermal Backfill	0.7
Fluidized Thermal Backfill (FTB)	0.6 - 0.7
Thermal Sand Backfill	0.44 - 1
Torpedo Sand	0.9
Duct/Pipe Thermal Resistivity (°C-m/W)	Duct/Pipe Thermal Resistivity (°C-m/W)
Fiberglass Duct (FRE)	4.8
Polyvinyl Chloride Duct (PVC)	4.0 - 7.0

Polyethylene Duct (PE)	3.5
Thermoplastic Pipe Coating	3.5 - 4.5
Insulation Thermal Resistivity (°C-m/W)	Duct/Pipe Thermal Resistivity (°C-m/W)
Crosslinked Polyethylene (XLPE)	3.5 - 4.0
Ethylene-Propylene-Rubber (EPR)	4.5 - 5.0
Impregnated Paper (HPFF & SCFF - Paper)	5.0 - 6.0
Laminated Paper-Polypropylene (HPFF & SCFF - LPP)	5.5 - 6.5
Factors (%)	Factors (%)
Load Factor	75 - 100
Power Factor for Insulation (tan-Delta)	Power Factor for Insulation (tan-Delta)
Crosslinked Polyethylene (XLPE)	0.0001 - 0.005
Ethylene-Propylene-Rubber (EPR)	0.002 - 0.08
Impregnated Paper (HPFF & SCFF - Paper)	0.002 - 0.0045
Laminated Paper-Polypropylene (HPFF & SCFF - LPP)	0.0007 - 0.0027
Dielectric Constant for Insulation	Dielectric Constant for Insulation
Crosslinked Polyethylene (XLPE)	2.1 - 2.5
Ethylene-Propylene-Rubber (EPR)	2.5 - 4.0
Impregnated Paper (HPFF & SCFF - Paper)	3.3 - 3.7
Laminated Paper-Polypropylene (HPFF & SCFF - LPP)	2.5 - 2.9

Notes:

(a) If the actual ambient temperatures or thermal resistivities for native soil are determined, those values should be used instead of the assumed values.

(b) The thermal resistivity of backfill materials vary based on individual utilities specifications for different backfills.

(c) These typical values represent those used by utilities in PJM’s territory for underground and submarine transmission lines with a burial depth of 15 feet or less.

10.0 REFERENCES AND SOURCES

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