SHIELDED POWER CABLE

APPLICATION OVERVIEW

Shielded power cable is employed to transfer electrical energy between two points without exposed conductors or electric fields. The energy which can be transferred through a buried power cable is limited by the maximum system operating temperature and, therefore, the ability of the cable system to dissipate heat into the soil. Electrical conduction losses go as the square of the current, and dielectric losses go as the square of the voltage between the conductor and grounded shield. However, dielectric losses can be made relatively small, so that economics normally favors use of higher voltages and lower currents in order to limit conduction losses. The cable operating voltage is usually dictated by the transmission or distribution system voltage, while conductor cross section and the number of cable circuits installed are usually dictated by the required steady-state ampacity and, in the case of transmission circuits, contingency requirements.

Two cable technologies currently compete in both the distribution and transmission cable markets: solid dielectric cable and laminar dielectric cable. Solid dielectric cable is made by extrusion of multiple layers of polymer over a metallic conductor, while laminar dielectric cable is made by taping mulitple layers over a metallic conductor.

STRUCTURE AND MATERIALS

Shielded power cable consists of a metallic conductor of copper or aluminum, a semiconducting (resistive) screen or shield surrounding the conductor, a dielectric medium, a semiconducting screen or shield surrounding the dielectric, a

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 1999 John Wiley & Sons, Inc.

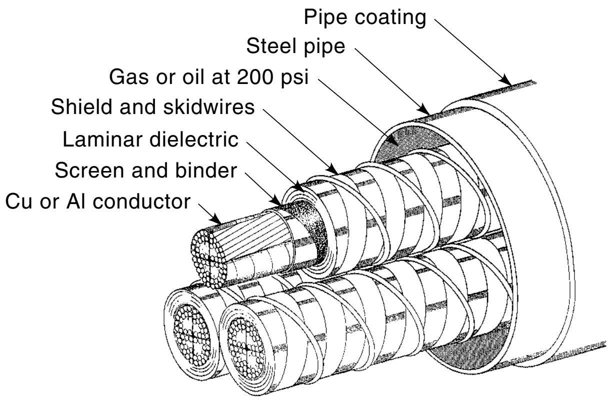

Figure 1. Structure of a HPFF (high-pressure, fluid-filled) cable. In an HPFF cable system, three cables are contained in a steel pipe filled with alkylbenzene or polybutene dielectric fluid pressurized to about 200 psig. The pressurized dielectric fluid is essential to the dielectric integrity of the cable. (Figure courtesy of USi.)

metallic ground shield capable of carrying shield and fault currents, and a mechanical protective structure which depends on the application. Figure 1 shows the structure of a typical high-pressure pipe-type cable, while Figs. 2 (a) and (b) show the structure of typical distribution cables.

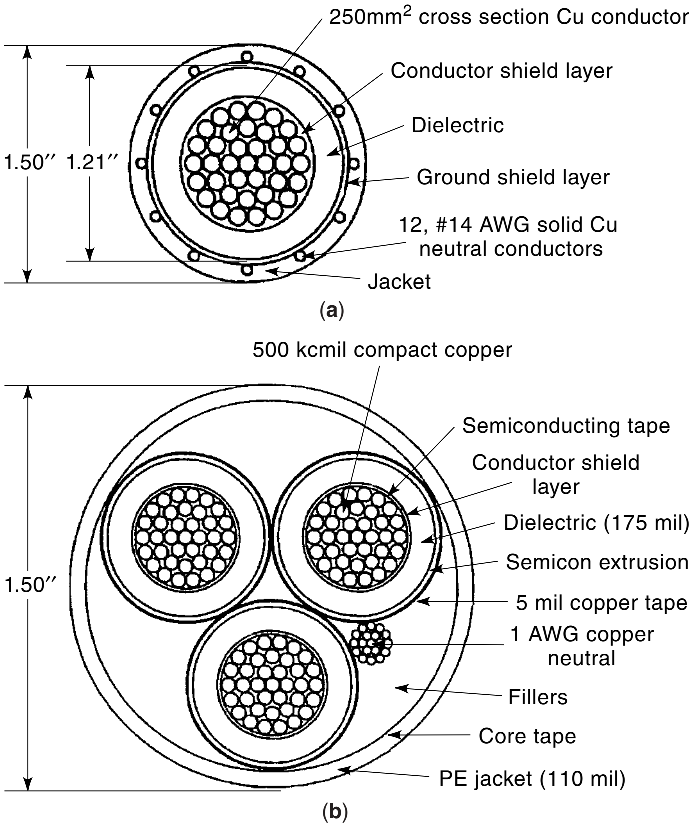

Figure 2. Two examples of solid dielectric distribution cable: (a) a typical distribution cable phase, and (b) a three-phase bundle. Such cables can be configured in a wide range of topologies depending on the application. (Figures courtesy of the Kerite Corporation.)

The Conductor

The conductor of a shielded power cable is stranded for flexibility and to reduce skin effect losses. For laminar pipe-type and extruded cables, small sizes have concentric stranding while medium sizes may be compact round, compacted by rolling or drawing to reduce diameter. Copper conductors with cross sections larger than 500 mm^2 (1000 kcmil) are usually segmental where the strands are divided into four or more segments in a manner designed to transpose radially layers of the strands to minimize losses. The strands of aluminum conductors oxidize, which limits current transfer between strands and allows larger concentric and compact sizes, up to 1000 mm^2 (2000 kcmil) before segmental constructions are favored. Concentric copper conductors employing enameled strands have been used successfully, but difficulties with jointing and terminating have limited their use.

Three-conductor laminar distribution cables may use 120 degree sector-shaped conductors to reduce the overall cable diameter. Self-contained laminar transmission cables require a hollow core conductor as a channel for the movement of the pressurized dielectric fluid. Copper conductors for early EHV laminar transmission cables were coated with tin or lead alloy to minimize catalytic interaction with the mineral fluids used to impregnate the paper dielectric. This practice is not necessary with the newer polybutene or alkylbenzene dielectric fluids.

Semiconducting Shields

Metallic conductors are not necessarily smooth. Any asperity on the conductor would cause a high field region in the adjacent dielectric if the dielectric were applied directly over the asperity. A resistive layer compatible with the dielectric is normally applied between the conductor and dielectric to provide a smooth interface between the conductor structure and the dielectric. Carbon-loaded paper tapes are used with laminar fluid-impregnated dielectrics while a carbon-loaded polymer is normally employed with bulk dielectrics such as cross-linked polyethylene (XLPE) or filled ethylene propylene copolymer (EPR). These resistive interface layers are referred to as semiconducting material or semicons.

For transmission class cables which operate at high electrical stress, the geometric field at the semicon-dielectric interface can be in the range of 15 kV_{rms}/mm, so that the smoothness of the interface becomes an important issue. To this end, “super smooth” and “super clean” semicons have been developed for XLPE-based solid dielectric cable. Semiconducting materials represent a high-technology aspect of shielded power cable in that they must maintain relatively stable properties over a wide range of temperature and time.

The Dielectric

A wide variety of dielectrics has been employed, ranging from early dielectrics of fluid-paper or natural rubber to modern dielectrics such as fluid-impregnated paper-polypropylene laminate (PPP), filled EPR, and XLPE. The latter three dielectrics, along with conventional fluid-impregnated paper, dominate present shielded cable dielectrics and will be discussed in turn.

Fluid-Impregnated Dielectrics

Refined mineral fluid impregnated paper is among the earliest and remains among the most forgiving of high-voltage dielectrics. Such insulation is widely employed in cables and transformers. The kraft process paper employed is specially manufactured for the purpose with controlled density (typically about 0.8 gm/cm^3), thickness (ranging from 60 μm (2.5 mils) to 260 μm (10.5 mils), and minimal ion content. The primary advantages of such laminar dielectrics are lack of correlation of defects from one layer to the next, segmentation of the fluid with a porous paper structure which minimizes the likelihood of conducting contaminants lining up in the electric field and causing breakdown, the ability of the system to fill any defects with the dielectric fluid, and some degree of mobility of any products produced by undesirable electrical activity such as partial discharge. These properties combine to produce an outstanding and very forgiving high voltage dielectric. For example, during the dissection of high voltage cables employing oil-paper dielectric, insects have been found taped into the cable during manufacture, and this did not cause failure of the cable in service.

Fluid-impregnated laminar paper dielectrics range widely and include:

Solid-type dielectrics which employ high viscosity impregnants to operate without applied pressure at moderate electrical field. This type of cable is limited to distribution applications at voltages up to 46 kV.

High-pressure fluid-filled pipe-type cable (HPFF) dielectrics which employ a high-viscosity fluid to impregnate three laminar dielectric cable phases installed in a steel pipe which is pressurized with a medium viscosity dielectric fluid to about 1.3 MPa (200 psig). As a result of the high operating fluid pressure, HPFF cables are very robust, and these cables operate at high electric fields.

Self-contained laminar dielectric cable (SCFF) dielectrics which are impregnated with low viscosity fluid, operate at moderate fluid pressure (100 kPa to 500 kPa or 15 psig to 75 psig), and operate at high electric fields. Because of the low operating pressure, these cables require thinner tapes near the conductor, and great pains are taken to prevent any air or gas from entering the cable after impregnation.

Recently, HPFF cable has been manufactured with PPP dielectric with increased dielectric strength and reduced dielectric loss relative to Kraft process paper. PPP dielectric allows a reduced insulation wall operating at very high electrical fields. The reduced dielectric wall has the advantages of increased conductor size for a given cable diameter and reduced thermal resistance between the conductor and dielectric fluid. The reduced dielectric loss of PPP dielectric becomes an important factor for very high voltage (EHV or 345 kV and above) cable. Together, the improved properties of PPP dielectric result in increased cable ampacity (current carrying ability) for a given pipe size.

High-pressure gas-filled cables (HPGF) which employ dielectric fluid-impregnated paper which is placed in a steel pipe filled with nitrogen gas at about 1.3 MPa (200 psig). This technology is well developed up to 138 kV but has not been applied at higher voltages. The nitrogen pressure must be sufficient that the gas in the butt gaps between paper tapes can withstand the electric field without discharge.

Solid Dielectrics

In the context of shielded power cable, the term *solid dielectrics* is used to indicate bulk dielectrics which are homogeneous at a macroscopic level. Cable employing such dielectrics is manufactured by extrusion. The principal solid dielectrics presently employed to manufacture shielded power cable are filled EPR and unfilled XLPE.

XLPE Distribution Cable. Cross-linked polyethylene (XLPE) is a semicrystalline polymer with substantial volumes of amorphous and crystalline polymer intimately mixed. The crystallites melt in the temperature range from 80°C to 110°C, which results in a thermal expansion of about 15% over this temperature range and a drop in the mechanical yield stress from about 50 MPa at room temperature to less than 1 MPa at 110°C. XLPE cable is usually rated to operate to 110°C to 130°C, and the large thermal expansion at elevated temperatures complicates greatly cable and accessory design. The implications of repeated melting and recrystallization of XLPE on long-term dielectric performance are not presently known.

XLPE distribution cable has gone through about four generations. The first generation was manufactured using carbon-impregnated cotton tape semiconducting shields. The cut edges of these tapes acted as wicks to conduct water into the dielectric and enhanced a phenomenon known as water treeing (1,2). Water treeing results from growth of a dendritic pattern of electrooxidized tracks within the dielectric which reduce the dielectric strength and eventually cause failure of the cable. Thus, the first generation of XLPE cable started to fail after about 7 years of service as opposed to the expected life of over 30 years. The second generation of XLPE cable employed extruded polymeric semiconducting shields; however, the semicon compounds employed were manufactured with relatively dirty carbon black with a high ion content which migrated into the XLPE dielectric and enhanced water treeing which again resulted in premature failure of this cable generation. The third generation of XLPE cable employed “super clean” semiconducting compounds, while the fourth generation employed water tree resistant XLPE dielectric (TR-XLPE), often with “super clean” semicons. Third and especially fourth generation XLPE distribution cables appear to be performing well in the field. Dealing with the problems created by the first and second generation cables, which have a replacement value in the billions of dollars, has become a significant industry-wide issue. The problems with early generations of XLPE cables also caused a substantial shift by the utility industry toward EPR cable.

EPR Distribution Cable. Ethylene propylene copolymer (EPR) is a generic term for a wide range of copolymers which can also include polyethylene and other polymers in the formulation. EPR compounds are widely used to manufacture utility distribution and industrial cable up to about 69 kV but find limited use at 115 kV to 138 kV. In an unfilled state, the EPR copolymer base of EPR dielectric is gummy and without structural integrity. The EPR is heavily filled with a range of materials which typically include specially treated clay, “red lead”, and zinc oxide to formulate a practical dielectric with excellent high temperature capability, moderate dielectric loss, and excellent resistance to water treeing-induced failures. Cable manufacturers and compound suppliers formulate differing EPR cable compounds with various claims to superiority, which provides a basis for product differentiation and customer loyalty. This has resulted in higher prices for EPR cable than for XLPE cable, where the XLPE tends to be a commodity supplied by relatively few compound manufacturers. The primary advantages of EPR-based cables are (i) increased flexibility, (ii) increased emergency operating temperature, and (iii) freedom from water-treeing induced failure. Undoubtedly, the latter has been the primary reason for increased market share of EPR in spite of a higher price than for equivalent XLPE cable. The primary disadvantage of EPR relative to XLPE is increased dielectric loss which becomes economically appreciable at voltages above 15 kV.

Transmission Class Cable. Solid dielectric transmission class cable (115 kV to 550 kV) is generally manufactured from XLPE with a watertight jacket so that water treeing is not an issue. However, the XLPE employed in modern transmission class cable is operated at substantially higher field (up to 15 kV_{rms}/mm) than distribution cable (≈3 kV/mm), with the result that the dielectric must be much cleaner (i.e., free from contaminants). As well, the semicon–dielectric interfaces must be very smooth. To this end, the XLPE employed in transmission class cable is often either made at the site of cable manufacture or is extruded through a fine mesh and repelletized using deionized water for cooling at the site of cable manufacture to assure freedom from contaminants which might be introduced during manufacture and, especially, shipping. The semiconducting compounds employed are classified as "super smooth" in that the carbon fillers are well dispersed without levels of agglomeration which result in filler particles protruding from the semicon into the dielectric.

Given the need to reduce the dielectric thickness of XLPE-based transmission cable in order to increase the conductor size and reduce the thermal resistance between the conductor and environment, the dielectric withstand of XLPE cable dielectric is of great interest. A range of measurements indicate that typical XLPE cable dielectric degrades rapidly at an ac field in the range of 250 kV_{peak}/mm or 175 kV_{rms}/mm and degrades very little at slightly lower fields. Such a high field can only exist around a microscopic defect in the dielectric as the power dissipation at such a field would cause thermally induced failure in a macroscopic region. The 175 kV_{rms}/mm degradation field is in contrast to the highest solid dielectric cable design stresses which are in the range of 15 kV_{rms}/mm, about an order of magnitude lower. Relatively short lengths of cable designed for operation in the region of 15 kV_{rms}/mm have minimum as-manufactured ac breakdown fields in the range of 40 kV_{rms}/mm as determined using a 3-parameter Weibull distribution.

MANUFACTURE

Laminar Dielectric Cable

The stranded conductor is formed in any of a range of configurations, although compact segmental conductors are most common for transmission class laminar dielectric cable, as they tend to minimize ac losses. The conductor is generally bound with a stainless steel binder tape. The conductor is passed through a taping machine which contains a taping head that holds 10, 12, or 16 pads, each lying in a radial plane. The paper tape from each pad is guided onto the cable by a series of rollers under a carefully controlled tension in order to apply the desired configuration of semiconducting and paper (or PPP) tapes. Taping must be designed carefully, and tension and moisture content of the tapes must be controlled, so that as the cable comes off the taping machine, the cable can be wound onto a reel without causing buckling of the tapes. Any buckling of the tapes would destroy the cable. Detailed equations have been developed which provide the basis for taping of laminar dielectric cable.

The reel of taped cable is placed in a large vacuum oven, where it is vacuum dried and then impregnated with dielectric fluid, operations which require a week or more. Jacketing depends on the cable type. HPFF cable would normally have a stainless steel tape over the ground semiconducting tapes. This tape would be interculated with a metalized polyester tape to form a moisture seal which limits the entrance of water vapor while the cable is in transit, but does not prevent the flow of dielectric fluid into and out of the dielectric during thermal cycles in service within the pressurized cable pipe. One or two stainless steel, brass, or zinc "D" shaped skid wires are applied over the moisture seal assembly to facilitate the pulling of the three cables into the steel pipe. Typical pulling lengths are 1500 ft to 3500 ft (500 m to 1100 m), but pulls in some submarine installations have exceeded 8000 ft (2700 m).

Self-contained cable would receive a metallic jacket (lead, aluminum, stainless steel, or brass). Bedding layers are used to protect the dielectric from the high temperatures during the extrusion of the lead or aluminum sheath or application of a corrugated aluminum, stainless steel, or brass sheath and to cushion the cable to protect it during installation. The bedding tapes must contain fine metallic wires to provide a continuous electrical connection between the ground tapes of the cable and the metallic jacket, otherwise discharges between the ground tapes of the cable and the metallic jacket are likely to cause cable failure in service.

Solid Dielectric Cable

Distribution solid dielectric cable is normally manufactured using a triple head extruder to apply the conductor semicon, dielectric, and ground semicon sequentially during a single pass through an extruder. The temperature of the extrusion is controlled carefully to avoid cross-linking of the dielectric within the extruder head. First and second generation XLPE distribution cables were then passed through a catenary in which the dielectric was cross-linked using steam to heat the polymer and control its temperature. The high-pressure steam employed in this step tended to cause saturation of the dielectric with moisture and the formation of numerous microcavities which enhanced water treeing during service. Third and fourth generation XLPE distribution cables generally employed dry curing using heated gas or silicone oil. The cable is next cooled. Earlier generations of cable employed water cooling while more recent manufacturing methods use other fluids. One limitation of the catenary form of cross-linking is that the dielectric hangs on the conductor during heating and cross-linking. As the dielectric becomes increasingly thick for higher voltage designs, it starts to sag off. This is generally not a problem for distribution cable but becomes a problem for transmission class cable. The cable is then jacketed. In the case of distribution cables, this means application of ground wires or a taped ground shield usually covered with a polymeric jacket for protection. In the past, many cables were installed without a jacket; however, installation of unjacketed cable has often resulted in greatly increased neutral corrosion and is no longer considered to be advisable.

Transmission class solid dielectric cable is also manufactured using a triple extruder; however, the dielectric is usually too thick to be cross-linked using a conventional catenary. At least three methods have been developed to manufacture transmission class cables with thick dielectrics. These are:

Long land die, where the cable coming out of the extruder enters a heated tube or die in which it is cross-linked. The conductor tension is adjusted to minimize settling during cross-linking, and lubricants are applied to the die to facilitate motion of the dielectric through the die. The pressure within the die is substantial, which probably minimizes formation of cavities within the dielectric. However, the cross-linking reaction results in some gas generation, and this gas is trapped within the cable during curing in the long land die. After manufacture, the cable must be degassed in an oven for an extended period of time which depends on the dielectric thickness.

Catenary within a liquid, where the catenary passes through a heated liquid such as silicone fluid. The displaced weight of the liquid supports the cable and avoids sagging of the dielectric on the conductor during curing.

Vertical curing column, where the cable exiting from the extruder head passes vertically down a curing column, which again avoids sagging of the dielectric on the conductor.

As noted, the dielectric for transmission class cable (especially above 138 kV) is generally of higher purity than employed for distribution cable. This is often achieved through manufacture of the dielectric at site of cable manufacture or purifying procedures undertaken at the site of cable manufacture. Such procedures include XLPE pellet inspection systems which inspect each XLPE pellet optically for impurities, extrusion through a fine mesh, and repelletizing. Such extrusion must be undertaken prior to adding the cross-linking agent, as the temperatures achieved during extrusion through an adequately fine mesh would cause cross linking.

The cable production rate depends on the time required for cross-linking and drops precipitously for the thick dielectrics required for 500 kV class cable. The time for degassing also increases rapidly with dielectric thickness, to weeks for 500 kV class cable.

ACCESSORIES

Accessories consist of the additional components beyond the cable which are required to implement a cable system, the most important of which are terminations and splices. Cable terminations provide an interface between the cable and another system function, such as connection to overhead transmission, to a power transformer, or to substation switchgear. Because the electric field at which the cable dielectric operates is generally substantially higher than the field of any other system component, the termination generally performs two functions:

- expanding the separation of the cable ground shield from the cable dielectric in a manner which does not cause an excessive electric field
- providing grading between the cable conductor and the expanded ground shield so that the field along this path does not exceed the breakdown field of the medium in which the interface is placed (air in the case of a cable-to-air termination, dielectric fluid in the case of a cable-to-transformer termination, etc.).

These two functions are often performed with separate structures, for example, a stress cone to expand the distance between the cable dielectric and ground shield and a capacitive grading structure to grade the field along the interface which connects the conductor to the expanded ground shield.

Distribution Cable

Over the history of electric power distribution, a wide range of cable constructions and dielectrics has been employed, including a great deal of lead-jacketed, oil-impregnated paper cable which has been very reliable as long as the lead jacket maintains its integrity. Very old distribution systems, such as those in most major cities, contain a wide range of primary distribution cable, including lead covered oil-paper, lead covered solid dielectric, and solid dielectric. Oil-paper cable is extremely reliable as long as the dielectric remains impregnated and dry. Splices for such cable usually involve sealing the ends of a copper or lead sleeve to the cable's lead jacket by wiping with molten lead, an operation which requires highly skilled trades persons. A specialized market exists for joints which connect lead jacketed oil-paper cable to solid dielectric cable while protecting the oil-paper dielectric from moisture ingress.

In North America, most distribution cables are at present manufactured with EPR or XLPE dielectric. Accessories for such distribution cable are available from a range of companies and are relatively inexpensive. As distribution cable is deployed on an extensive basis, accessories must be installed easily and quickly by crews with only moderate levels of training. A number of technologies compete for both terminations and splices, two of which are heat shrink and cold shrink. In both cases, a polymeric structure is slipped over the prepared cable and shrinks into the cable. In one case, the shrinkage is achieved by applying heat to the polymeric structure, and in the other case, a spiral wound core is pulled out of the polymeric structure to allow it to shrink onto the cable. This technology has been applied to both terminations and splices. Such devices usually involve a molded structure with multiple layers of varying dielectric constant and conductivity which combine to achieve acceptable grading, especially in the region where the semicon layer of the cable is terminated, which tends to be the most critical region in a splice or termination design. In the case of cable-to-air terminations, grading of the exterior surface is also a consideration; however, as a result of the large ratio of the BIL (which is often taken to be the voltage for about 5% probability of lightning impulse breakdown) to the operating voltage, the exterior structure must be sized much larger than required to withstand normal ac operating voltage, which makes grading for normal operation relatively simple.

A wide range of specialized cable accessories is available for distribution cable, such as load break elbows which facilitate live connection and disconnection of energized cables from transformers and other apparatus.

Transmission Cable

Accessories for transmission cable are much more complex than for distribution cable as a result of the much higher fields at which transmission cables operate as well as the greatly reduced ratio of BIL to operating voltage.

Fluid-Impregnated Cable. As noted, HPFF cable dominates transmission class systems presently installed in North America. HPFF systems are complex and require a range of accessories including cable joints, cable stop joints, trifurcators, terminations, polarization cells, cathodic protection, and pressurizing systems.

HPFF cable joints are constructed by penciling the laminar dielectric, using some form of compression connector or welding to connect the conductors, and hand taping over the connector region to reconstitute the cable insulation. A greater thickness of insulation is employed in the splice region than in the cable, and a three phase splice is normally housed in a greatly enlarged enclosure (around 0.6–0.9-m or 14–20-inch diameter) relative to the cable pipe (14–27-cm or 5.5–10.75-inch OD). Specialized stop joints are employed to facilitate fluid sectionalizing of a cable to limit leaks, etc.

As noted, a cable-to-air termination serves two purposes, (i) to separate the ground shield from the conductor in a manner which does not cause excessive field within the dielectric, and (ii) to grade the air adjacent to the termination (the region between the separated cable conductor and ground shield) in a manner which prevents flashover during operation. HPFF cable terminations are designed in a range of configurations. Laminar oil-paper dielectrics are very strong radially (through the paper layers) but relatively weak longitudinally (along the layers). Thus, one function of a termination is to separate the ground shield from the cable conductor in a manner which does not result in excessive longitudinal field in the dielectric. This is generally achieved using a stress cone in the form of a paper roll with a log–log taper at the bottom. This taper is used to increase the diameter of the cable dielectric while maintaining constant longitudinal field in the cable dielectric and stress cone roll. The log–log taper starts at the OD of the cable dielectric and increases in radius with the cable shield carried along the outer radius of the taper. Such a paper roll must be carefully designed and cut to maintain the correct taper, which can now be achieved using computer-controlled slitters. The paper roll is perforated to produce the log–log taper on one end. The roll is normally wound on a mandrel which is slightly larger than the cable dielectric over which the roll will be placed. The roll is then slipped over the prepared cable and tightened down on the cable. The perforation is then torn to produce the log–log taper.

At 115/138 kV, grading of the air adjacent to the termination is often achieved with very simple structures made of high dielectric constant materials such as porcelain or with condenser structures in which foils are wound into layers of the paper roll to form a capacitor structure with tapered ends which grades the field along the taper at the top and bottom of the structure. One end grades the field in the region where the ground shield is terminated, while the other end grades the field in the air adjacent to the termination. At 230 kV and higher voltages, condenser structures are sometimes employed, but use of a capacitor stack along the inside of the termination enclosure is more common. Approximately 25 or more spiral-wound capacitors are commonly employed, depending on operating voltage. Since the outside diameter of such a capacitor is a single foil, it represents an equipotential surface with the potential changing in a step-wise manner from one capacitor to the next. However, this ragged potential grading is smoothed by the high dielectric constant of a porcelain enclosure so that the grading in air is acceptably smooth. A trifurcator separates the three cables within the cable pipe into three cables, each of which is in a separate pipe, as required to implement single phase terminations.

The steel pipe of an HPFF cable has an insulating coating but also requires cathodic protection to control corrosion. Cathodic protection involves placing a potential of -0.7 V to -0.8 V on the pipe which counters electrochemical corrosion potentials. This requires separating the pipe from ground. However, if a fault should occur, the pipe carries much of the fault current and must be grounded. These two requirements are achieved using a polarization cell, which is an electrochemical cell with an ionic boundary layer between the electrolyte and cell plates, which supports a few volts with very low leakage but breaks down to become a very low impedance conductor for higher potential differences.

An HPFF cable system requires a pumping plant with fluid storage reservoir to maintain fluid pressure and to accept and supply fluid with thermal expansion and contraction of the fluid in the pipe. Such a pumping plant is relatively expensive and requires constant monitoring and periodic maintenance. As a result, HPFF cable systems tend not to be economic for short runs where the pumping plant constitutes an appreciable fraction of the overall cost.

A wide range of specialized accessories allow direct connection of HPFF transmission class cable to GIS (SF_6 insulated substations), power transformers, etc.

Solid Dielectric Cable. The structure of transmission class solid dielectric cable differs from distribution cable in that solid dielectric distribution cables are usually manufactured with a strippable ground semiconducting layer which greatly eases preparation of the cable for a splice or termination. Transmission class solid dielectric cables employ a ground shield which is cross-linked to the dielectric. This makes removing the ground shield in a manner which does not cause a defect or excessive field in the cable dielectric very difficult. As a result, development of splices for solid dielectric cable has generally been one voltage level behind cable development. As well, splices and terminations for transmission class solid dielectric cable have been far less reliable than the cable. For the higher voltage classes, some early splice designs required a crew six weeks to install a single three phase splice. Given the critical nature of accessories for transmission class solid dielectric cable, many experts feel that such cable is not presently appropriate for mix and match accessories: that is, the accessories should be supplied by the cable manufacturer as part of a cable system.

Early generations of transmission class solid dielectric cable accessories were generally fluid filled. As environmental concerns are a major driving force for the gradual transition from HPFF and SCFF cable system to solid dielectric cable systems, the market is demanding dry solid dielectric cable accessories, and while the design of dry transmission class accessories is difficult at the higher transmission voltages, progress toward such accessories is evident in the literature.

THERMAL DESIGN

As noted, power transfer by shielded power cable is normally limited by the maximum operating temperature of the dielectric. The power which can be transmitted without exceeding the maximum operating temperature is determined by the effective thermal resistance from the conductor to the soil. In the case of transmission cable, emergency ampacity requirements often determine cable system design and when an additional cable circuit must be added to maintain system security.

Distribution Cable

Thermally, EPR cable is superior to XLPE cable. EPR cable can operate to about 150°C without serious degradation. XLPE cable is often rated to 130°C emergency operating temperature but is better restricted to between 90°C and 110°C. XLPE is a semicrystalline material, and the crystallites melt between 85°C and 100°C, which results in substantial softening of the material, a precipitous drop in the mechanical yield stress, and thermal expansion of about 15%. For these reasons, XLPE cable is best operated below 90°C although standards generally require an emergency operating temperature between 110°C and 130°C. EPR cable has relatively high dielectric loss, is not used above 138 kV, and is rarely used above 69 kV. Optimizing ampacity is not a major issue for most distribution circuits although it can be very important for station feeders.

Transmission Cable

Ampacity is very important for transmission class cables. As a result, thermal cable design is a major part of overall cable system design (3). The effective soil thermal resistance is very important to cable ampacity. As part of cable system design, the soil thermal resistance along a cable route is surveyed in situ using a thermal resistance probe about 2 m long, often with simultaneous measurement of soil thermal resistivity at three depths. Soil samples are often taken along the route in order to measure soil thermal resistance versus moisture content in the laboratory. To achieve the desired effective thermal soil resistance based on the measured properties of the native soil, the cable trench/trench backfill is designed to achieve the desired worst case effective thermal resistance.

Soil thermal resistivity is a strong function of soil type and soil moisture content. Soil thermal stability is also important, as some soils have a tendency to dry out under sustained heat flux while other soils maintain relatively constant and stable thermal resistivity down to very low moisture concentrations (4). In many climates, soils are likely to dry completely during certain times of the year, so that a cable system must be designed on the basis of dry soil. Good thermal backfills, such as well-graded limestone screenings, have a thermal resistivity in the range of 120°C-cm/W under dry conditions and remain thermally stable to about 3% moisture content (i.e., they can sustain substantial heat flux without a change in thermal resistance). Weak concrete is probably the best widely available thermal backfill, with a dry thermal resistance in the range of 70°C-cm/W. It also has the advantage of being pumpable so that it can be used to fill a duct into which a cable may be installed under a roadway.

Book cable system ampacity ratings are generally based on worst case conditions: that is, worst case initial steady-state operating temperature, worst case soil thermal resistivity, etc. Where book ratings based on such conservative assumptions do not provide adequate ampacity or where ampacity needs to be increased above such conservative book ratings, two technologies are available. At the design stage, the cable can be forced cooled (5). In the case of HPFF cables, this means that the dielectric fluid is circulated through fluid-to-air heat exchangers to remove heat from the cable system without dissipating the heat in the soil. In some cases, refrigeration systems are also employed.

Under retrofit conditions, real time rating is possible (6). As applied to HPFF transmission class cable, a real time rating system consists of hardware which measures the pipe temperature and the soil temperature away from the pipe. Given this information along with the conductor current and a thermal model for the cable system within the pipe, the soil thermal resistance can be identified and tracked in real time using an appropriate computer system and software. Such measurements and computations are generally made at a number of potentially worst case cross sections of the cable system. Given the soil thermal resistance and knowledge of the actual cable operating conditions, real time ratings can be computed for quasi-steady state and short-term emergency operating conditions. Short-term emergency current ratings for a HPFF cable are generally much greater than steady-state ratings as a result of the very long thermal time constant of such a system which is in the range of 200 hours. As the need for additional circuit ampacity is generally based on emergency operating conditions and ratings, installation of a real time rating system at a cost in the range of $100,000 can often forestall the need to install an additional cable circuit at a cost of many millions of dollars. Real time ratings systems for HPFF cable are commercially available and have been deployed on an appreciable number of cable systems. Table 1 shows typical ratings for HPFF cable systems.

Table 1. Typical Single Circuit Ampacity for HPFF Transmission Cable Systems

	Paper Insulation		PPP Insulation	
Voltage	Pipe Size	MVA	Pipe Size	MVA
138 kV	8.625″	281	6.625″	288
230 kV	8.625″	443	8.625″	478
345 kV	10.75″	623	8.625″	694
550 kV	12.75″	779	8.625″	1023

Notes: Conductor size = 2500 kcmil (1250 mm^2) Cu, maximum conductor temperature = 85 °C, earth ambient = 25 °C, earth thermal resistivity = 90 °C-cm/Watt, loss factor = 0.624. Data computed using "USAmp+" Ampacity Program from USi.

INSTALLATION

Distribution Cable

Distribution cable is either direct buried or installed within ducts. Since distribution cables usually are not heavily loaded, thermal design is not normally a major consideration, although problems have occurred where multiple station feeders pass through a limited number of ducts which are surrounded with particularly poor thermal backfill (e.g., sand). Application of directional drilling to distribution cable installation has made great strides within the past decade, in part through the support of the Electric Power Research Institute (7).

Transmission Cable

In North America, most transmission class cables are used to bring electric power to the core of large cities. New York City has the largest concentration of transmission class power cables (345 kV and 138 kV). Other such cables are installed in Boston; Chicago; Washington, DC; Toronto; and so on. Most of the presently installed transmission class cables are HPFF: that is, three cable phases installed within pressurized, dielectric fluid filled steel pipe. This construction is favored because the pipe can be installed in sections before the cable is pulled into the pipe. This minimizes the time that a trench associated with one pipe section must be open, thereby minimizing disruption of traffic and commerce in the urban environment in which most cables are installed. Most future transmission class cables will be either HPGF or solid dielectric cable in order to avoid the risk of dielectric fluid leaks and spills. Solid dielectric cable is being installed in pipes or ducts to reduce construction costs in most of the large urban areas.

Installation of the cable pipe is a major part of overall cable system expense and can cost as much as $300/m in congested urban environments. After the cable pipe has been installed, the cable is pulled between manholes which are typically separated by between 300 and 1000 m, after which the cable sections are spliced together in each manhole. Cable pulling is a delicate operation with careful control of tension during the pulling operation. Pulling lengths must be reduced when bends are present along the pull.

Once the cables are installed, spliced together, and terminations are installed, the pipe is evacuated and pressurized with dielectric fluid which can be mineral oil-based, polybutene, or alkylbenzene. The requirements for HPFF dielectric fluid are very strict and include gas absorption properties, pour and flash temperatures, oxidation stability, etc. (8). Such highly refined organic fluids tend to have low toxicity and, increasingly, are regulated less stringently than less refined hydrocarbon fluids.

CABLE SYSTEM TESTING, MAINTENANCE, AND DIAGNOSTICS

Distribution Cable

No maintenance is normally required for solid dielectric distribution cable. However, as a result of the many failures which occur in early generations of XLPE distribution cable, many utilities conduct tests of such cable on a routine basis in order to weed out cable which is likely to fail in the near future. A range of tests has been used for this purpose, including dc, low frequency ac, and ac. Definitive data are now available which indicate that while use of dc testing on a new XLPE cable of any generation is not damaging, dc testing of XLPE cable with water trees is damaging in that the likelihood of cable failure after the cable is placed back into service increases substantially as a result of the dc testing (9,10). This is the result of space charge injection at water tree sites during the dc test which increases the electric field when the cable is energized with ac. For this reason, dc testing is being abandoned. Alternatives include low frequency ac, power frequency ac, and power frequency ac with on-line partial discharge location. The latter has shown considerable promise for detecting bad sections of water treed distribution cable and has proved its value for locating defective splices.

A system has also been developed for rejuvenation of water treed distribution cable (11). A silicone fluid is injected into the stranded cable conductor and permeates into water trees growing from the conductor semicon where it gels by reacting with the water in the water tree. This system has generally proved effective for water trees growing from the conductor semicon. Application is complicated by the need to bring the fluid around splices. The system cannot be applied to strand-blocked cable (cable in which the space between conductor strands is filled to inhibit migration of water down the strands).

Transmission Cable

Solid dielectric transmission cable generally requires little testing or maintenance. As past experience demonstrates that accessories for solid dielectric transmission cable are far less reliable than the cable, substantial effort has focused on developing diagnostics which can be applied after installation and which can monitor accessories on-line. For example, X-ray imaging has been applied to solid dielectric cable splices. Sensitive systems for on-line partial discharge monitoring of solid dielectric cables and especially cable splices have been developed.

Some HPFF cable systems are now over 60 years old and still function very reliably. The primary determinant of system aging appears to be pipe corrosion. The only routine maintenance for an HPFF cable system relates to accessories such as terminations and pumping plants. On very rare occasions, the dielectric fluid might be dried or degassed, but this would be the exception rather than the rule.

Diagnostics, such as dissolved gas analysis, which are employed for power transformers, have been applied to HPFF cable systems with limited success as a result of the distributed nature of such systems.

Leak detection and location is the primary diagnostic and maintenance issue for HPFF cables. Until recently, leak detection was based on excessive pump operation or low reservoir level. Such leak detection is relatively crude and involves release of substantial fluid before a leak is detected. More recently systems have been developed which involve installation of sensitive flow meters in the cable system which allow comparison of thermally and leak induced fluid flows with a software model of such flows. A systematic difference between the model and measurements indicates a leak. By using such systems, a leak rate in the range of 4 liters per hour can be detected with a total leakage of about 100 L (12).

Early methods of leak location involved use of directional flow indicators placed within the pipe at valve locations. However, such methods are not very accurate as thermally induced flows can be greater than lead-induced flows. More recently, leaks have been located successfully using mixtures of perfluorocarbon tracer gases and very sensitive detection apparatus.

CABLE SYSTEM OPERATION

The primary concern during operation of an HPFF cable system is to maintain adequate fluid pressure, as such a system will certainly fail dielectrically if it is operated for an appreciable length of time unpressurized. The pumping plant and cable pressure are normally monitored with appropriate alarms.

Operation of most cable systems without real time rating is based on "book" ratings which may vary seasonally. The book ratings specify the maximum steady-state current and the maximum emergency overload current versus time. In the presence of a real time rating system, the ratings would be available from an on-line computer system, would change periodically, and would be a function of the present state of the cable system. If the soil thermal conductivity is greater than the worst case condition or if the cable/soil temperature is lower than the assumed worst case condition, the short-term emergency ratings will be much greater than fixed book ratings based on worst case assumptions. As noted, the increased contingency ratings generally achievable through real time rating can forestall the need for an additional cable circuit.

CABLE SYSTEM RELIABILITY

Solid Dielectric Cable

For all cable system voltages, accessories are much less reliable than the cable. In the case of distribution cable in the range of 13.2 kV to 35 kV, the accessories are basically reliable as long as they are installed properly, and the unreliability experienced usually results from a discrepancy between the level of installation skill assumed by the accessory manufacturer and the level of installation skill actually available in the field. That having been said, some systematic failures from accessory design errors have occurred. At 69 kV and above the design of both splices and terminations become problematic and a very high level of skill and meticulous workmanship is required to implement a reliable splice or termination.

Laminar Dielectric Cable

Laminar dielectric cable is a mature technology with demonstrated reliability. The most recent development in this technology is the use of paper polypropylene (PPP) laminate dielectric which facilitates reduced insulation wall, increased conductor size, and increased ampacity. However, the increased electric field within the dielectric complicates the design of splices and terminations. Still, an appreciable number of PPP dielectric HPFF cable systems have been installed with generally good experience. The greatest problem associated with laminar dielectric cable systems is fluid leakage, and this problem is increasing with time as a result of increasingly stringent environmental regulation and aging/corrosion of cable pipes. At 115/138 kV, HPGF cable is a well-proved alternative to HPFF cable which is environmentally more acceptable and is providing direct competition for solid dielectric cable systems.

System Cost and Comparative Reliability

Cable-based transmission and distribution systems generally cost at least an order of magnitude more than comparable air-insulated (overhead) transmission systems. While cable systems may be more reliable than air-insulated systems in terms of the number of outages, any outages that do occur are likely to last longer than for an air-insulated system.

In all cases, solid dielectric cable systems are substantially less reliable than cable systems based on fluid-impregnated paper dielectric. At distribution voltages, solid dielectric cable systems are much less expensive than systems based on fluid-impregnated paper dielectric. At transmission voltages (115 kV and above), economics depend on system length and construction. However, systems based on laminar dielectric cable are generally comparable in price to systems based on solid dielectric cable. At 115/138 kV, HPGF and solid dielectric cable system costs are comparable. Laminar dielectric cable system technology is very mature while transmission class solid dielectric cable is in relative infancy. The reliability of solid dielectric cable systems (especially accessories, which have been the most problematic aspect of such systems) will certainly improve, and the cost of such systems will probably drop.

BIBLIOGRAPHY

1. M. T. Shaw and S. H. Shaw, *IEEE Trans. Electr. Insul.,* **EI-19**: 419, 1984.
2. J. J. Xu and S. A. Boggs, The chemical nature of water treeing: Theories and evidence, *IEEE Electr. Insul. Mag.,* **10**: 29, 1994.
3. S. A. Boggs et al., *Underground Cable Thermal Backfill,* Pergamon Press: Canada Ltd, 1982.
4. S. A. Boggs et al., Measurements of soil thermal properties: Techniques and instrumentation, *IEEE Trans. Power Appar. Syst.,* **PAS-99**: 747, 1980.
5. D. W. Purnhagen, Designer's handbook for forced-cooled high-pressure oil-filled pipe-type cable systems, EPRI Project RP 7801-5, Final Report EL-3624, July 1984.
6. J. S. Engelhardt, R. J. Nelson, and T. F. Brennan, The application of real-time monitoring and rating to HPOF pipe cable systems, *IEEE Trans. Power Deliv.,* **4**: 850–856, 1989.
7. T. J. Rodenbaugh and M. Kirby, Guided horizontal drilling: A primer for electric utilities, Electric Power Research Institute Publication No. OIL: TR107687.
8. Mineral Oil used in Electrical Apparatus, ASTM D3487.
9. N. Srinivas and B. S. Bernstein, Effect of dc testing on XLPE insulated cables, *Proc. 4th Int. Conf. Polymer-Insulated Cables,* JICABLE 95, Paris, France, 1995.
10. N. Srinivas, B. S. Bernstein, and R. Decker, Effects of dc testing on ac breakdown strength of XLPE-insulated cables subjected to laboratory accelerated aging, *IEEE Trans. Power Deliv.,* **5**: 1643–1657, 1990.

11. G. J. Bertini and W. M. Chatterton, Dielectric enhancement technology, *IEEE Electr. Insul. Mag.,* **10** (2): 17–22, 1994.
12. D. W. Purnhagen, DRUMS leak detection for HPFF pipe-type cable systems, EPRI Project RP 7900-01, Final Report TR-105250, August 1995.

STEVEN A. BOGGS
University of Connecticut
JOHN S. ENGELHARDT
Underground Systems, Inc.

SHIELDING ELECTROMAGNETIC FIELDS. See ELECTROMAGNETIC SHIELDING.

SHIFTERS, PHASE. See PHASE SHIFTERS.

SHOCKS, ELECTRIC. See ELECTRIC SHOCKS.

SHORTEST PATH. See CRITICAL PATH ANALYSIS; DYNAMIC PROGRAMMING.