Chapter 10
Structural Design and Performance of XLPE for Cable Insulation

Timothy J. Person, Saurav S. Sengupta, and Paul J. Caronia

1 Introduction

Not long after the invention of the telegraph in 1839, the race to long-distance and even trans-Atlantic communication began. In many applications including submarine and buried wires, a suitable electrical insulation system was required. Early insulation systems were based upon strips of India rubber. By the late 1840s, gutta-percha (a natural gum) was utilized as wire insulation due to the ability to easily melt and coat wires in combination with good electrical insulating properties. As electrical demand increased in the late 1870s with a drive to electric lighting, excessive deformation of natural rubber insulations was experienced due to the low-temperature softening of such materials. Rigid cables designed by Edison with a wrapped conductor isolated by bitumen inside an iron conduit provided a solution for urban lighting. In the 1890s, an electrical cable system was introduced which employed a paper insulation which was saturated with oil. Paper-insulated cables enabled power cable voltages of 10 kV and higher and remained the primary power cable insulation technology for decades with various design improvements. Paper-insulated cable proved reliable, but had several drawbacks associated with the use of oil impregnant and the complexity of forming joints. While these issues were later addressed with the use of polyethylene as an electrical insulation, paper-insulated cables are still utilized in many power cable applications today [1–4].

The discovery of ethylene polymerization is credited to Fawcett and Gibson in 1933, although German scientists claimed to have documented production of $(–CH_2–)x$ from diazomethane chemistry as early as 1897. Fawcett and Gibson, however, produced polyethylene directly from ethylene in a high-pressure process in which

---

T. J. Person · S. S. Sengupta (✉) · P. J. Caronia
The Dow Chemical Company, Collegeville, PA, USA
e-mail: SSSengupta@dow.com

J. Thomas et al. (eds.), *Crosslinkable Polyethylene*, Materials Horizons: From Nature to Nanomaterials,
https://doi.org/10.1007/978-981-16-0514-7_10

oxygen had (accidentally) been introduced into the methane. Difficulties in reproducing the initial experience were later explained by the work of Perrin and colleagues in 1935, where the presence of trace amounts of oxygen as an initiator for the polymerization reaction was recognized, and ultimately resulted in a granted patent in 1937 [5–10].

Polyethylene was rapidly industrialized and utilized as an electrical cable insulation as early as 1942. By 1947, it was utilized in 15 kV cable for residential power distribution. Polyethylene provided excellent insulating properties, reduced electrical losses and reduced installation and maintenance costs compared to paper-insulated cables [2]. The application use temperature (ampacity) could be increased with polyethylene-insulated power cables relative to paper-insulated cables, but temperatures were still limited by the softening and deformation of the polymer as temperatures exceeded 70 °C [1]. This temperature limitation was later addressed with the advent of crosslinked polyethylene (addressed in the following section).

The fundamental design elements of polyethylene-insulated cable have not changed significantly between its early use and the present day, yet there has been continual drive to increase voltage (as a means to reduce current and associated resistive losses) for more efficient power delivery.

Electricity is generated typically in the range of 2–30 kV depending on the source of energy and then stepped up to higher voltages using a step-up transformer. Electricity is then transmitted at high voltages (69–700 kV) using underground insulated cables or over-head metal wires. In nearby neighborhoods, a step-down transformer reduces the voltage and distributes the power to houses at 5–46 kV. Underground cables further distribute the power/electricity to residences or commercial end users at lower voltages (500 V–5 kV) for consumption and use. The cables employed in such a grid can be physically located underground (UG), overhead (OH) or in submarine environments (entrenched in the sea bed or laying of the ocean floor). The common classification of these power delivery systems is depicted in Fig. 10.1.

UG, OH and sea cables require protection from the elements and reliable operations over a long period of time. The designs of such cables have evolved over time and can vary based on the specific needs of utilities and end users. The common design elements are presented in Fig. 10.2. The conductor is chosen by the utilities based on the grid (power demand, voltage and ampacity, and thermal designs) and connectivity requirements, and it is not in scope for this discussion. The jacket materials (which were not always employed in early cable designs) are typically thermoplastic-formulated polyethylenes sufficient to provide mechanical protection and to protect the metallic neutral or ground materials from corrosion.

The insulation shield is typically formulated with carbon black in a polymer matrix and serves the following purposes:

(a) Prevents partial electrical discharge between the metallic neutral or ground materials and the cable insulation,
(b) Provides uniform ground potential around the insulation,
(c) Minimizes charge buildup on outside of cable for operator safety,

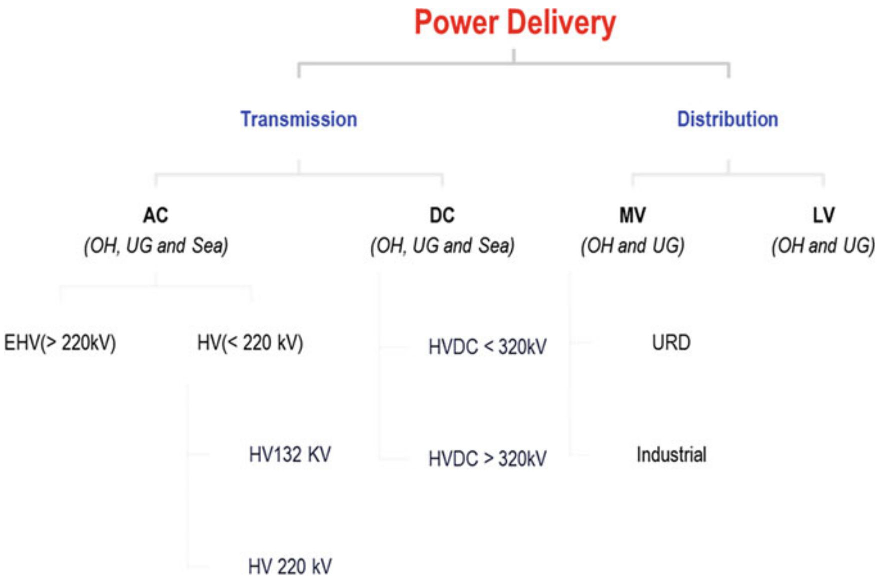


Fig. 10.1 Common classification of the power delivery systems

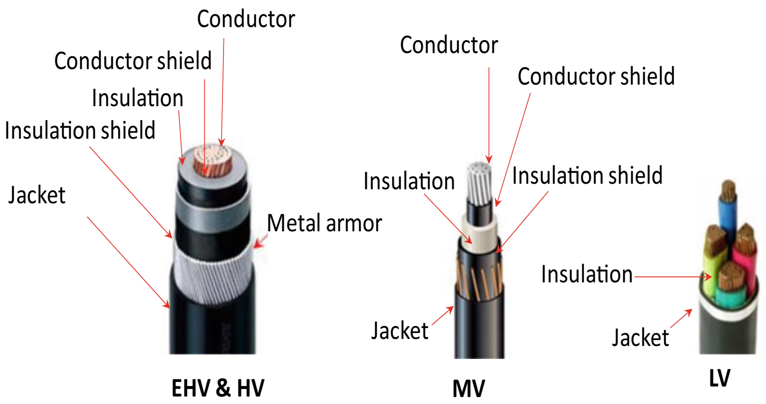


Fig. 10.2 Typical construction of XLPE cables

(d) Provides a material layer of intermediate conductivity/permittivity between the insulation and metallic neutral or ground materials which must be removed without damage to the underlying insulation for effective installation of splices, terminations and joints.

The insulation requirements and technical aspects will be further discussed in this chapter, but generally three key considerations come into play:

(a) Thermo-mechanical properties,

(b) Ease of fabrication,
(c) Dielectric properties:

- Dielectric losses,
- Dielectric strength.

2 History of XLPE Insulation

In 1945, Pinkney and Wiley filed a patent describing a means to crosslink polyethylenes using an organic peroxide. Their work demonstrated gel formation in an ethylene-vinyl acetate copolymer, and potential use as a wire coating was contemplated [11]. However, Precopio and Gilbert have been recognized with the invention of crosslinked polyethylene and filed patents for radiation-induced crosslinking of polyethylene in February of 1955 and peroxide-initiated crosslinking of polyethylene in May of 1955 [12]. These patents included the demonstration of crosslinking of ethylene homopolymers. In an interview published in 1999, Gilbert described how dated and witnessed notes were essential in resolving the issues at the US Patent Office [13, 14].

The work of Precopio and Gilbert spread quickly to colleagues in the General Electric Company. By 1957, Vostovich and Bailey had filed a patent describing the process of crosslinking polyethylene and producing coated wires [15]. In this process, peroxide is mixed into a polyethylene composition and extruded onto a wire, and then immediately contacted with pressurized steam as a means to initiate the crosslinking of the polyethylene. Ward filed a separate patent in 1958, in which a carbon-black-filled semiconductive layer was introduced over the conductor and crosslinked, followed by the polyethylene insulation which could also be crosslinked [16]. Even at this time the presence of the intermediate semiconductive layer was known to reduce the electric field gradient and reduce the presence of corona discharges in high-voltage cables. The insulation and semiconductive layers could be extruded as thermoplastic followed by crosslinking, pre-crosslinked and milled followed by extrusion, or could be applied as thin crosslinked and stretched (oriented) tapes around the conductor and subsequently heated to shrink into void-free layers. Irradiation crosslinking was noted as particularly useful for the thin extruded tapes.

Another means of crosslinking polyethylene utilizes silane functionality incorporated into the polymer. In 1961, Union Carbide Corporation demonstrated that trialkoxysilane functionality could be introduced into an ethylene polymer, and the resulting polymer could be crosslinked upon heating to cause a reaction between the silane groups [17]. It was later determined that these ethylene-vinylsilane copolymers could be effectively crosslinked with moisture and a silanol condensation catalyst. The silane-functionalized polyethylene can be formed as a copolymer of ethylene and vinyl silane in a high-pressure polymerization process or can result from grafting of vinyl silane to polyethylene using a radical-initiated process (typically initiated using organic peroxide). The silane-functionalized polyethylene can then be melt processed along with a separate masterbatch compound to form an insulation layer; the masterbatch will introduce a suitable catalyst, typically of organotin or sulfonic acid type. Grafting and melt extrusion may also take place simultaneously in a single process to form an insulation coating. The insulated wire can then be crosslinked as moisture diffuses into the insulation layers, either under ambient conditions or under accelerated conditions through the use of a water bath or sauna. The diffusion-limited crosslinking rate often limits the application of moisture-cure polyethylene to lower voltage applications and thinner insulation thicknesses [18].

Crosslinking of polyethylene provided enhanced thermo-mechanical deformation resistance and enabled an increase of the use temperature, and thereby the ampacity, of insulated power cables. Today, crosslinked polyethylene-insulated cables are rated for maximum of 90 °C (and in some cases 105 °C) conductor temperature. Where overload conditions are allowed, these temperature ratings can reach 130 °C (and in some cases 140 °C) for a limited time throughout the cable lifetime.

The incorporation of mineral fillers into crosslinkable polyethylene provided a means to impact the thermal and mechanical properties of the resulting compounds. Crosslinkable filled ethylene-propylene elastomers were first commercially available in the early 1960s. The presence of the filler will generally reduce electrical properties (increase electrical losses and reduce breakdown strength), but filled elastomeric insulating compounds based on ethylene propylene rubber (EPR) have become common in many power distribution applications where a high degree of flexibility, heat resistance and chemical resistance is desired [19].

3 Insulation Requirements

Two key reasons for using XLPE insulation are its high dielectric strength and very low dissipation factor characteristic. The high dielectric strength of XLPE is a key feature for its use in power cables rated from 5 kV to 500 kV with an intrinsic breakdown strength reported at above 200 kV/mm [28] and well made XLPE insulated distribution cable having a breakdown strength in excess of 26 kV/mm (based on minimum within ICEA S-94-649 standard). The low dissipation factor characteristic is reflected by a global experience that XLPE insulated cables should have a dissipation factor of less than 0.10% between room temperature to 130 °C and electrical stresses up to 20 kV/mm. For water tree retardant crosslinked polyethylene (TR-XLPE), which will be discussed shortly, its specialized formulation technology includes the incorporation of polar components and it is generally not able to meet this dissipation factor requirement. For TRXLPE, the industry has accepted a dissipation factor of less than 0.50% between room temperature to 130 °C and electrical stresses up to 10 kV/mm.

In the 1970s, with the growing use of crosslinked polyethylene in power cables, the industry became aware of the electrical degradation phenomenon of treeing; both electrical treeing and water treeing. Though there are a number of variables that impact XLPE treeing, one factor common to both electrical and water treeing is the impact of electrical stress enhancements due to contaminants. Based on the recognition that contaminants can have a role in a XLPE insulated cable's live performance, some industrial specifications include specific cable insulation inspection requirements. Other industrial specifications address insulation cleanliness indirectly with requirements on a cable's minimum AC withstand voltages, minimum impulse strength and maximum partial discharge requirements. Defects, as due to contaminants, would make achieving the required properties difficult. Based on the differences in operating stresses and conditions between transmission and distribution class cables, there are differences in the cleanliness requirements for the XLPE materials used in these cables [20, 21].

Additionally, compound manufacturers monitor the cleanliness of XLPE compounds, wherein a selected quantity of material is extruded into a molten tape and then examined by associated contamination detection and sizing equipment. As this is a destructive test, a small quantity of material is tested such that tape inspection is generally one component of an overall assessment of insulation cleanliness.

For cables that will be exposed to moisture as well as be under electrical and mechanical stress, XLPE insulation can undergo a phenomenon known as 'water treeing.' Water trees in the XLPE insulation are generally considered to be degraded, chemically oxidized structures that are observed as a dendritic pattern of water-filled micron and sub-micron-sized cavities. As water trees grow, the electrical stress on the insulation can increase to the point where an electrical tree initiates at the tip. Once initiated, electrical trees grow rapidly and lead to catastrophic failure of the cable [22–25].

In order to avoid or minimize this phenomenon, two different approaches are taken. One option is to modify the design of the cable to eliminate the possibility of water or moisture ingression. This is done by the use of a metal sheath resulting in a so-called dry-design cable [1]. Although successful, this is a relatively expensive solution, especially for a medium voltage cable installation. It can also impact cable flexibility and the complexity and difficulty of the cable installation process. The alternative is to use a more cost-effective 'wet design,' whereby the moisture-impervious metal sheath is eliminated and replaced by diffusion-resistant polyethylene jackets, water-absorbing tapes and conductor strand filling compound. However, in this case, the cable insulation needs to be more robust toward the growth of water trees in a wet electrical aging environment. As a result, the wet design cable preferably employs a water tree retardant insulation. The vast majority of wet cable designs are used in the manufacture of medium voltage (6–46 kV) cables [2].

The key industry specifications for MV through EHV cables are outlined below, and a summary of the requirements as related to insulation contamination is discussed.

HV/EHV Specifications

- IEC 60840: Power cables with extruded insulation and their accessories for rated voltages above 30 kV up to 150 kV—Test methods and requirements,
- IEC 62067: Power cables with extruded insulation and their accessories for rated voltages above 150 kV up to 500 kV,

- AEIC CS9: Specification for Extruded Insulation Power Cables and their Accessories rated above 46 kV through 345 kVac,
- ICEA S-108-720: Standard for Extruded Insulation Power Cables Rated Above 46 Through 500 kV,
- Chinese National Standard/Specification GB/T 11017 for 110 kV Cable,
- Chinese National Standard/Specification GB/TZ 18890 for 220 kV Cable,
- Chinese National Standard/Specification GB/T 22078 for 500 kV Cable.

MV Specifications

- IEC 60502 Part 1 and 2: Power cables with extruded insulation and their accessories for rated voltages from 1 kV up to 30 kV,
- CENELEC Harmonization Document (HD 620),
- AEIC CS8: Specification for Extruded Dielectric Shielded Power Cables rated 5 through 46 kV,
- ICEA S-94-649: Standard for Concentric Neutral Cables Rated 5 through 46 kV,
- ICEA S-97-682: Standard for Utility Shielded Power Cables Rated 5 through 46 kV,
- Chinese National Standard/Specification GB/T 12706 for 1 kV up to 35 kV Cables.

The IEC specifications do not have a cleanliness specification or requirement. However, the factory cable electrical requirements (AC Breakdown and Impulse) would limit contaminant sizes in order to pass the tests. The AEIC/ICEA specifications have insulation contamination requirements for MV, HV and EHV cables. The method for examining the insulation as well as the requirements is outlined in the specifications. The insulation contamination requirements vary based on cable voltage class. In China, the Chinese National Standard/Specifications also have contamination requirements on the incoming insulation compound. These requirements also vary based on the cable voltage class.

4 Choice of Insulation Materials for Cables

Insulation in cables is a vital layer to prevent the leakage or loss of power from being transmitted. This layer demands the following balance of properties [1]:

a. Excellent Electrical Properties:
    - Low Dielectric Constant,
    - Low Power Factor,
    - High Dielectric Strength.

b. Excellent Moisture Resistance:
    - Low Moisture Vapor Transmission.

c. High Resistance to Chemicals and Solvents.

Table 10.1 Available materials for wire and cables

Material	Common name
Thermoplastic	
• Polyvinyl Chloride	PVC
• Polyethylene	PE
• Polypropylene	PP
• EA/VA coploymers	EEA/EVA
• Chlorinated polyethylene	CPE (also crosslinked)
• Thermoplastic elastomer	TPE
• Nylon	Nylon
• Fluorocarbon polymers	PTFE, FEP, CTFE
• Polyurethanes	
Crosslinked	
• Polythylene	XLPE
• Rubber	NR, SBR, Butyl, Silicone
• Neoprene	
• Nitrilie-Butadiene/Polyvinyl Chloride	NBR/PVC
• Chlorosulphnated polyethylene	CSPE
• Ethylene propylene rubber	EPR/EPDM

The materials commonly used in wire and cable are listed in Table 10.1. PVC has been widely used as a non-metallic jacketing material since its introduction in 1935. Low cost, ease of processing and excellent combination of overall properties including fire and chemical resistance are some of the value propositions for this material. It has a fairly linear molecular structure with 5 to 10% crystallinity [26]. Usually, it is formulated with plasticizers and stabilizers to maintain good flexibility, heat resistance and low temperature properties. However, under high current fault conditions, the insulation may be permanently damaged by melting or loss of plasticizers. Polypropylene also offers unique properties as a jacket or insulation material and has electrical and chemical resistance properties similar to those of polyethylene. From the perspective of mechanical properties, it is harder and stiffer than polyethylene [27]. It is also characterized by a higher melting point and poor low temperature properties as compared to polyethylene. Nylon presents an interesting blend of properties and is a tough material but stiff in cold weather conditions. It has excellent resistance to hydrocarbon fluids, lubricants and organic solvents but not toward strong acids. It is almost exclusively used as jacket material because of its sensitivity to moisture [28]. Sometimes fluorocarbon polymers are used in special cable applications. They offer low flame ability, excellent abrasion and abuse resistance properties. They are characterized by a high dielectric constant but offer good resistance to moisture, weathering ozone and UV radiation. It is not a material of choice in high-voltage insulation because of propensity to degrade under corona discharge conditions [29]. Rubbers are often used as insulation materials where excellent resistance to oil, harsh chemicals and flexibility is needed. Polyethylene as an insulation offers excellent electrical properties and good chemical resistance and is characterized by a very low moisture vapor transmission rate. These polymers offer excellent UV stability when formulated with proper grade of carbon black or UV stabilizers. These materials are unaffected by ozone as compared to the rubbers and offer excellent retention of functional additives as compared to PVC products. They offer a good balance of toughness versus flexibility and are easy to fabricate via extrusion. In some cases, these may be foamed by chemical or physical foaming agents. The polyethylene materials are inexpensive and readily available on small and large scales. Upon proper formulation, they offer very long-life performance and reliable cable operation. The upper use temperatures are limited for polyethylene materials since they start to soften from 90 °C.

Consider the dielectric constant of polyethylene (ε) which is related to the polarizability of the material (α) through the Clausius–Mossotti–Debye equation [30]:

$$\frac{(\boldsymbol{\varepsilon}-1)\boldsymbol{M}}{(\boldsymbol{\varepsilon}+2)\boldsymbol{\rho}}=\frac{4\pi\boldsymbol{N}\boldsymbol{\alpha}}{3} \tag{1}$$

where N is the Avogadro number,

ρ is density,

M is the molecular weight of a material.

The polarizability is usually understood as contributions from electronics and due to the orientation of permanent electrical dipole moments. According to Debye, this orientation is proportional to the dipole moment of the molecule. In polyethylene, these diploes may arise from CH bond moments, C=C bond moments and impurities. The dielectric constant is affected by the temperature, frequency and pressure since these parameters affect the variables used to describe this property. From a molecular structure standpoint, density and hence crystallinity have a direct impact on the dielectric constant.

Even when segmental level polarization is taken into account, the fact that polyethylenes have hydrocarbon structures and are essentially non-polar may lead one to believe that no dielectric loss occurs over the useful range. Although the losses are low compared to existing materials, they are still measurable and are an important consideration for the design of the insulation materials. The dielectric losses are always more sensitive to small concentration of polar groups present in the material. This property is the result of relaxation of the polar impurity groups which seem to be always present. These polar molecules are often free to rotate even though they may be confined to a rigid lattice. Such behavior is to be expected in polyethylene where the intermolecular forces are weak and appreciable portion of the structure is amorphous.

Design considerations on current-carrying capacity (ampacity) as well as voltage ratings for any given cable system allow the use of very limited materials as insulation in power cables. The dielectric heating and energy loss in power cables are given by:

Table 10.2 Electrical properties of insulating materials

Material	Dielectric constant	Dielectric loss
Air	~1	~0.0000
Teflon	2.1	0.0002
PE	2.4	0.0005
Nylon	3.5	0.0065
PVC	6	0.1000

$$\text{Power loss per phase} = 2\pi \text{fCU}_0^2 \tan\delta \qquad (2)$$

where f = supply frequency (Hz),
C = capacitance per core (F/m),
U_0 = voltage to earth (V),
tan δ = dielectric loss angle of insulation.

Table 10.2 lists the tan δ values for various common insulating materials and for the same type of constructions and under similar operating conditions also gives a relative idea of expected loss characteristics. The paper and oil materials have inherently low susceptibility toward discharges and treeing. As paper-insulated cable ages under load cycling and voltage stress, impregnated fluids migrate with temperature changes and lead to the formation of waxes and detrimental microvoids. This along with the complexity associated with splicing and terminating these cables places those at a disadvantage compared to solid extruded cables. While extruded cable has become the dominant technology, it is expected that paper/oil cables will continue to be utilized in some applications due to proven longevity. Polyethylene-based insulations have low loss characteristics and high dielectric strength which are advantages in this application. However, the cable environment impacts the susceptibility of polyethylene insulation to electrical discharges and treeing. This has led to the use of formulated compounds in this area to achieve the required performance.

The manufacture of power cables with extruded polyethylene insulation began with the use of thermoplastic polyethylene. In order to improve upon high temperature performance and achieve thermal stability, thermoset compounds such as XLPE came into use. There are mainly two classes of polyethylenes, linear and branched. The branched family of resins is made by a high-pressure reactor and is usually referred to as LDPE (low-density polyethylene). This was the original PE discovered in 1935 and has been prevalent in the power cable industry since its introduction in 1950s. Since then, other polyethylenes have been synthesized with different molecular architectures. Table 10.3 lists the various kinds of polyethylene available for use, their properties and year of development. LDPE resins are typically characterized by broad molecular weight distributions and long-chain branched (LCB) molecules. The other linear resins are noted for their narrow molecular weight distribution and short-chain branched (SCB) molecules.

Table 10.3 Different grades of polyethylenes

	Density (gm/cc)	Melting point (°C)	Crystallinity (%)	Developed year
LDPE	0.915–0.93	106–120	40–60	1935
HDPE	0.94–0.965	125–135	65–80	1955
LLDPE	0.91–0.94	120–125	40–60	1975
VLDPE	0.89–0.91	118–122	25–40	1983

Extruded cable manufacturing assets are usually designed to accept ready-to-extrude pellets which are fed in an extruder. A proper process control (and extrusion screw design) leads the compound to be melted and forced through a die-head arrangement that deposits the melt on the conductor core being passed through the crosshead. State-of-the-art cable extrusion processes consist of co-extrusion of three material layers over a metallic conductor (semiconductive inner shield, insulation and semiconductive outer shield) to form a cable core, which is subsequently crosslinked to increase the use temperature. After allowing the crosslinking by-products to diffuse out of the cable core, a metallic neutral ground is applied (typically wires wrapped helically around the core), and a thermoplastic protective jacket is extruded over the neutral to complete the cable construction. Curing or crosslinking is enabled through technologies such as peroxide crosslinking, silane crosslinking and radiation crosslinking. Peroxide curable insulation compounds are typically formulated with dicumyl peroxide as the radical initiator to allow for extrusion above the melt temperature of polyethylene with limited initiator activity, followed by crosslinking at elevated temperatures sufficient to dramatically increase initiator activity. This process of elevated temperature crosslinking is referred to as vulcanization. Following extrusion onto the conductor, the compound is exposed in a continuous vulcanization chamber to a pressurized high temperature environment. The environment can be high-pressure steam (about 250 psi) which yields a temperature of about 400 °F. Alternatively, dry nitrogen may be used to process the crosslinkable insulation at a pressure of about 150 psi when used in conjunction with a vulcanization tube wall temperature of approximately 650 °F. These high temperatures cause the peroxide to decompose into reactive free radicals. The pressure is required to reduce void formation from volatile peroxide decomposition by-products. A number of design and process configurations exist for the overall process and selected based on the type of cable being manufactured and volume requirements. The cable manufacturing process as discussed very briefly above imposes serious material properties consideration for the selection of insulation compounds. Most of the current cable manufacturing process is an optimized design around LDPE resins.

The final properties of solid crosslinked insulation at the molecular level can be roughly correlated with the molecular weight of the polymer (Mw). From the physical property data listed in Table 10.3, high-density polyethylene (HDPE) can be ruled out based on its higher melting point and density characteristics. Based on a first pass assessment, linear low-density polyethylene (LLDPE) on the other hand

Table 10.4 Comparison of LDPE and LLDPE flow properties

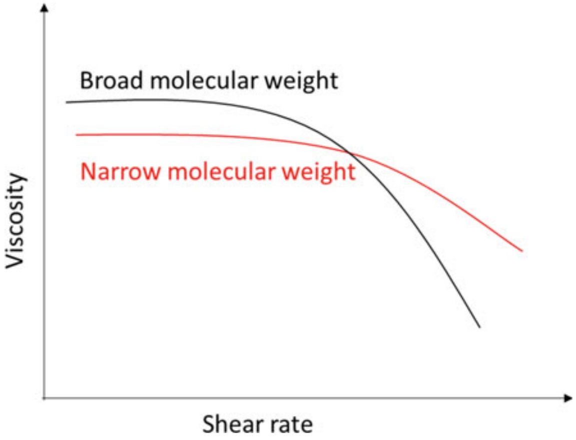
Mw	LDPE	LLDPE
(g/mol)	MI	MI
815,600	0.45	0.001
251,320	0.21	0.064
153,400	2.3	0.36
125,000	6.9	0.75

presents itself as a viable option for use as insulation material. Listed in Table 10.4 are melt indices of LDPE and LLDPE at various molecular weights. For any given molecular weight, the melt index (MI) of an LDPE resin is at least an order of magnitude higher than LLDPE resin that translates into an easier flowing material at the same melt temperature, or a similar flow at a lower temperature which can be an advantage when trying to limit premature crosslinking reactions.

Figure 10.3 shows the viscosity (Pa s.) dependence of typical LDPE as compared to that of linear PE resins as a function of shear rate (1/s). Narrow molecular weight distribution PE shows a prolonged Newtonian behavior. Broad molecular weight distribution allows higher low-shear viscosities (or zero shear viscosities) and lower high-shear viscosities (shear thinning). These are principal attributes that facilitate sag-resistance in the vulcanization process and ease of extrusion during fabrication, respectively. VLDPE resin made via Ziegler Natta process is very similar to LLDPE. This discussion suggests that in terms of processing ease, LDPE presents the best option in existing equipment.

Detailed study of crosslinking efficiency and scorch retardance had been carried out in the past with LLDPE and LDPE resins. It was found that increase in compound viscosity was enhanced with LLDPE due to the degree of polymer chain entanglement as compared to probability of intra-chain crosslinks in highly branched and more

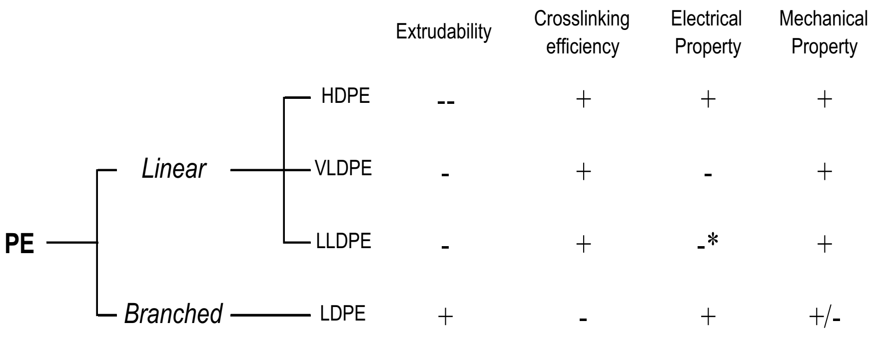
Fig. 10.3 Comparison of rheology of PE resins



tightly coiled LDPE. However, these resins performed poorly in terms of scorch retardance. LDPE resins presented a balance of cure and scorch retardance. This suggests that LLDPE being more efficient in the curing step would pose serious challenges in extrusion. Considering typical rheology and shear-thinning behavior of LLDPE, it is expected that it would require slightly higher melt processing temperatures in order to achieve the same output compared to LDPE and this will further aggravate any pre-mature crosslinking concerns. However, all studies were conducted using DCP as the peroxide initiator. Use of LLDPE may be conceived with different peroxides or mixtures having higher activation temperatures and tailored decomposition kinetics. The other option is to use conventional peroxides with coagents like AMSD.

Electrical performance limits the selection of base resins even further. Generally, LDPE has a dissipation factor of around 0.0005 as compared to LLDPE which can have an order of magnitude higher owing to catalyst residues from its synthetic process. Earlier experimentation had revealed that dissipation factor and breakdown strength of LLDPE were inferior compared to LDPE but acceptable. However, particular grades of LLDPE resins are available that meet the electrical requirements.

Choice of base resin for insulation compounds in power cables is governed by the balance of electrical properties (low DC/DF, high VR, high dielectric strength), mechanical properties (good elongation, LTB, crosslinked modulus at high temperature), functionality (high unsaturation) and flow properties (high shear thinning, high zero shear viscosity). These impact the cable manufacturing process as well as final cable properties like lifetime, flexibility, etc. Figure 10.4 presents a high-level comparison of available resins, based on the discussion above, from the standpoint of use in insulation materials. This analysis represents why LDPE resin is the material of choice in cable designs using current extruder cable fabrication equipment.



	Extrudability	Crosslinking efficiency	Electrical Property	Mechanical Property
HDPE	--	+	+	+
VLDPE	-	+	-	+
LLDPE	-	+	-*	+
LDPE	+	-	+	+/-

Fig. 10.4 Material selection for peroxide curable power cable insulation. * = selected resin grades with preferred catalysts can meet electrical performance requirements

5 Factors Affecting Dielectric Performance

An effective power cable insulation is one that enables efficient delivery of electrical power. Clearly, this delivery must first avoid an electrical breakdown or fault between the high potential conductor and the ground, throughout the expected lifetime of the cable. As a second aspect, the efficiency of the power delivery is focused on minimizing energy loss during the operation of the cable. If one is to discuss these aspects, it becomes important to first establish a general basis of electrical behavior of materials. Bartnikas and Eichhorn provide a detailed foundation, while only a few essential concepts are provided in the following section [31].

5.1 *Material Permittivity, Dissipation Factor and Conductivity*

Consider an ideal parallel plate capacitor separated by vacuum with charge, Q, at the plates under a steady voltage, V_o. The capacitance, C_o, is the ratio of the charge to the voltage, Q/V_o. When a dielectric material is placed between the plates, the voltage is reduced to V and the capacitance to Q/V. A material parameter, known as the relative permittivity (or dielectric constant), can be described as

$$\varepsilon_r = V_\mathrm{o}/V = C/C_\mathrm{o} \tag{3}$$

The reduction in voltage results from electric polarization of the material. Polarization occurs with the orientation of permanent dipoles within the molecular structure of the dielectric. Polarization may also be induced within non-polar materials, as an applied field will result in a displacement of the electron clouds within an atomic or molecular structure.

The above representation of the relative permittivity can also be termed the static permittivity and represents an equilibrium value. The rate of polarization is dependent upon the structure of the dielectric material (e.g., the strength of dipoles, atomic and molecular interactions, and crystallinity), and polarization contributes to dielectric loss. The permittivity is a complex quantity and can be expressed as $\varepsilon = \varepsilon' - j\varepsilon''$ where ε'' is related to the energy stored within the material and ε'' is related to energy dissipation or loss. When an alternating voltage is applied across a dielectric material, the resulting current can be separated into two components, one in-phase with the voltage and one leading the voltage by 90°. The leading current is the charging current of an ideal capacitor, while the in-phase current represents the loss current. The ratio of loss current to charging current, which is often equated to the ratio of dielectric loss to dielectric storage, $\varepsilon''/\varepsilon'$, is referred to as tan δ (tangent delta) or dissipation factor. However, materials are not ideal capacitors, and loss current measurements also include a conductivity component due to displacement of charge carriers. The conductivity, σ, defined as the ratio of current density to applied field, will have both an ac and a dc component. Thus, an apparent dissipation factor will then take the form of

$$\tan\delta = \sigma/\omega\varepsilon' = \varepsilon''/\varepsilon' + \sigma_{dc}/\omega\varepsilon' \tag{4}$$

where total conductivity $\sigma = \sigma_{ac} + \sigma_{dc}$. At high frequencies, the component associated with dc conductivity becomes negligible, while at very low frequencies the losses can become dominated by dc conduction. For further information on dielectric polarization and losses, the reader is directed to references by Bartnikas and Raju. Typical electrical properties of several polymeric materials are provided in Table 10.5, as reported by Raju. The table refers to volume resistivity, which is the inverse of conductivity [32, 33].

Table 10.5 Typical electrical properties of several polymeric materials as reported by Raju [28]

Material	Dielectric strength (kV/mm)	Volume resistivity (Ω cm)	Dielectric constant (–)	Dissipation factor ($\times 10^{-4}$)
Polyethylene (LDPE)	200	10^{16}	2.3 (50–60 Hz) 2.2 (1 kHz) 2.2 (1 MHz)	2–10 (50–60 Hz) 3 (1 kHz) 3 (1 MHz)
Polyethylene (HDPE)	200	10^{16}	2.35 (50–60 Hz) 2.4 (1 MHz)	2.4 (50–60 Hz) 2–7 (1 MHz)
Polyethylene (XLPE)	220	10^{16}	2.3 (1 MHz)	3 (1 MHz)
Polypropylene (biaxially oriented)	200	$3\text{x}10^{14}$	2.27 (50–60 Hz) 2.2 (1 kHz) 2.2 (1 MHz)	3 (1 kHz) 3 (1 MHz)
Polytetrafluoroethylene (PTFE)	88–176	10^{18}	2.1 (50–60 Hz) 2.0 (1 kHz) 2.0 (1 MHz)	2 (50–60 Hz) 1 (1 kHz) 1 (1 MHz)
Polyester (PET)	275–300	10^{18}	3.2 (1 kHz) 3.0 (1 MHz)	50 (1 kHz) 160 (1 MHz)
Ethylene-propylene diene rubber (EPDM)	20–	10^{16}	2.5–3.5 (50–60 Hz)	70 (1 kHz)
Silicone rubber	20–30	–	2.5–3.2 (50–60 Hz) 2.5–3.2 (1 kHz) 3.0–3.6 (1 MHz)	4–25 (50–60 Hz) 3–10 (1 kHz) 20–50 (1 MHz)

5.2 Electrical Breakdown

A large air gap represents an effective insulation, and bare overhead conductors suspended from poles or large towers serve this purpose very well. In this case, the cables are suspended far enough away from trees, structures, and ground so that the air is able to sustain the resulting electrical field without a breakdown. However, aspects such as aesthetics, vegetation management, right-of-ways, power delivery across large bodies of water, power theft and reliability in adverse weather conditions all represent drivers for underground or submarine power cables. Such applications require an insulating layer over the conductor which must also be able to sustain the electric field without a breakdown throughout the expected lifetime of the cable. Electrical breakdown of polymeric insulation is discussed in depth within [Dissado and Fothergill], with various breakdown mechanisms identified as electrical, thermal, electromechanical and partial discharge breakdowns. In the electronic breakdown, a high-energy charge carrier within free volume of the dielectric is accelerated by the applied field. The energy gained can become sufficient to damage the polymer matrix upon charge carrier collision or to result in ejection of a number of additional charge carriers (e.g., electrons), which themselves are accelerated due to the applied field. The result is an electron avalanche and numerous high-energy collisions resulting in failure of the polymer dielectric [34].

Polyethylene is recognized as having a high breakdown strength. The intrinsic breakdown strength of polyethylene has been estimated to be above 700 kV/mm, yet breakdown strength is reduced dramatically when practical volumes are electrically stressed [Fischer, 1976]. Such behavior has been attributed to the presence of critical defects and an increased probability of having a critical defect as the tested volume is increased. The similarity in the intrinsic breakdown strength was also observed in comparison with the peak ac to dc breakdown characteristics for a given low-density polyethylene. In that same work, various LDPEs with different average molecular weights were shown to exhibit an increase in breakdown strength with an increase in average molecular weight [35].

The breakdown strength of polyethylene has been observed to increase with increased density. This effect is consistent with free-volume breakdown mechanisms described in Dissado and Fothergill, as an increase in density effectively reduces the available free volume for such charge carrier acceleration. Additional aspects of crystalline morphology as related to breakdown strength have been studied through the use of polyethylene blends. Breakdown strength is also known to drop as the temperature is increased, where temperature not only assists in overcoming the energetic barrier to break bonds, but also contributes to the formation of more amorphous volume as the edges of crystallites begin to melt [36, 37].

A common method of characterization of polyethylene breakdown strength or initiation of a pre-breakdown phenomenon known as electrical treeing incorporates the use of needle-shaped electrodes into polyethylene blocks or samples of cable insulation. Breakdown stress has been approximated at 300 kV/mm in this manner. Using needle tips of different radii, researchers have also found a limitation in the expected breakdown due to geometric stress enhancement. It was found that a needle tip radius of less than 10 microns did not provide a further reduction in breakdown voltage. This was considered that local field decay becomes very rapid with smaller tip radii such that it may become more difficult to realize a critical electric field over a critical length to sustain a breakdown event. There is also evidence of injected charge near the needle tip which will provide effective field-screening to manage the local field and thus limit the localized damage. The combination of a critical tip radius (~10 μ) and a critical breakdown strength (~300 kV/mm) has become important elements utilized in the estimation of a critical-sized contaminant (addressed shortly) [38, 39].

Numerous studies have considered so-called voltage stabilizers of various functionalities which can be added to a polymer composition with the intent of capturing the energy of the high electrons and transforming it into a less damaging form of energy release. Various electron donor-acceptor structures have been studied based upon this hot-electron mechanism with varied degrees of success. Fused aromatic structures were found to be highly effective voltage stabilizers, yet their poor solubility in polyethylene brings concern of long-term effectiveness if the additive is fugitive. Functionalized aromatics such as alkylated pyrene and anthracene were also explored. Acetophenone is a known voltage stabilizing additive and is also a major by-product of the crosslinking of XLPE with dicumyl peroxide as an initiator. However, acetophenone is volatile and will slowly evacuate from the insulation layers of the XLPE cable, such that cable breakdown strength can be significantly reduced after the concentration of volatile by-products are reduced via a 'degassing' process. [This has raised some concern in the use of partial discharge testing as a cable manufacturing quality test before the cable is sufficiently 'degassed,' as a cable defect could be masked in the presence of acetophenone shortly after manufacturing. But later, that same cable could be delivered for installation with much lower levels of residual acetophenone, which enable the detection of that defect through positive partial discharge testing.] The effective voltage stabilizing nature of acetophenone led to further investigations of larger molecules with similar structures, such as benzophenone and various derivatives thereof with the intent of improving the solubility and finding a voltage stabilizing additive which was less fugitive. Voltage stabilizers continue to be a critical area of research, but have not yet made significant commercial impact. The benefits seen in the laboratory using highly divergent fields from wires or needle tips do not appear to have a significant effect on a manufactured cable [40–45].

5.3 *Impact of Contaminants*

While structural properties of polyethylene can impact electrical breakdown, the practical breakdown strength of polyethylene is still found to be much lower than the intrinsic values measured by Fischer. In order to better appreciate this, we must consider the presence of a contaminant within the polyethylene and the impact that it may have on the resulting breakdown strength. The properties of the insulation volume are no longer spatially uniform as the electrical properties of the contaminant can be much different than that of the insulation. In this case, the relevant material property is the permittivity, which relates the displacement field to the electrical field, $\mathbf{D} = \varepsilon\mathbf{E}$. The divergence of the displacement field is equal to the free charge density, such that div $\mathbf{D} = \text{div}\,(\varepsilon\mathbf{E}) = \rho$, which is a form of Gauss's law where the permittivity can still vary with position. Thus, for an example domain in which there is no free charge ($\rho = 0$), the spatial variation of the material permittivity will define the local electrical field. If the permittivity is spatially constant, then the field takes the form of the Laplacian, where div $\mathbf{E} = 0$. But, if a contaminant of differing permittivity exists within the domain, then large field enhancements can exist [33].

The field enhancements for contaminants of different shapes and permittivities have been calculated in this manner. The most common models are based upon ellipsoidal contaminant geometries. An expression for the stress enhancement as a function of assumed ellipsoidal geometry and contaminant permittivity is provided in Böstrom and appears to be an extension of the 1912 work of Larmor and Larmor.

$$\text{SEF} = 1 - \frac{1}{\alpha}\left\{\frac{1}{2}ln\left(\frac{\lambda+1}{\lambda-1}\right) - \frac{\lambda}{\lambda^2-1}\right\} \tag{5}$$

$$\alpha = \frac{1}{2}ln\left(\frac{\lambda+1}{\lambda-1}\right) - \frac{1}{\lambda} + \frac{1}{(k-1)\lambda\left(\lambda^2-1\right)} \tag{6}$$

$$\lambda = \frac{1}{\left\{1-\left(\frac{R}{a}\right)\right\}^{\frac{1}{2}}} \tag{7}$$

where R is the tip radius, a is the half-length of the major ellipsoidal axis, and k is the ratio of the permittivities of the contaminant particle to the matrix (originally focused on the impact of contaminants within the insulation). For a conductive ellipsoid, the value of k will be very high, such that the third term in the expression for α will become very small. [This equation has been reproduced here in corrected form, as a typographical error in the placement of the parentheses was noted within Böstrom. The corrected form above is now easily validated to yield the expected stress enhancement of 3 for a high permittivity spherical contaminant, which has been published by Bowers and Cath.] Bahder provides an alternate form for ellipsoidal contaminants with reference to the work of Larmor and Larmor, and Malik refers to yet a third representation with credit given to Bateman. Each of these models has been found equivalent to the representation provided above. The calculated stress enhancement factor for ellipsoidal contaminants of different permittivity ratios is shown in Fig. 10.5 [46–49].

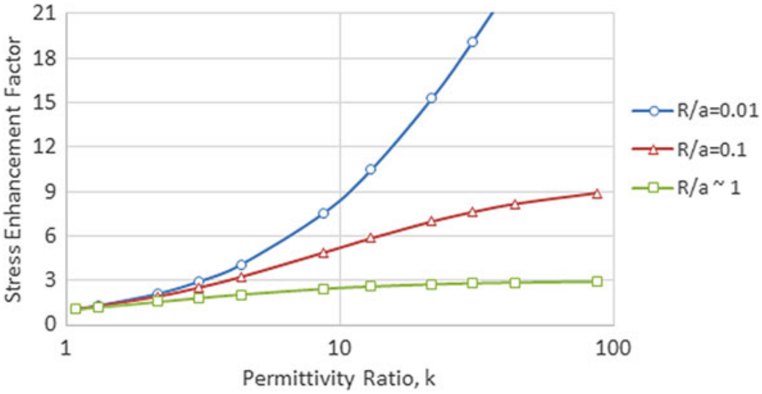


Fig. 10.5 Stress Enhancement Factor of an ellipsoidal contaminant as a function of shape and permittivity ratio

5.4 Electrical Aging

A high initial breakdown strength does not ensure that an insulation will sustain a high electrical stress over the lifetime of the cable insulation. Constant stress evaluations of time-to-failure (t) under different applied electrical fields (E) give rise to an aging correlation which has become known as the inverse power law. A plot of log E versus log t is found to yield a straight line (with a slop—1/n), such that the product $E^n t$ is constant. Values for the lifetime exponent, n, can range from 5 to 8 for distribution cable systems, but are typically 10–15 for XLPE insulation utilized in high-voltage applications [50].

One can also consider the constant in the inverse power law to represent a measure of lifetime, such that any increment of time at a given field will represent a fraction of that lifetime (or a degree of aging). Such concepts have been applied to step-wise or ramped stress evaluations as a means to characterize the parameters of the aging model in a shorter duration. The use of such concepts involves the assumption that the inverse power law is a reasonable approximation of material aging over the entire range of stress conditions and can lead to considerable uncertainty in the resulting estimates.

5.5 Critically Sized Contaminants

If one starts with the needle tests discussed by Ishibashi, which suggested 300 kV/mm as a critical failure stress during 15 min time steps, the inverse power law provides a means to define a critical stress for another duration such as that of a qualification test or the expected cable lifetime. Additional correction factors can be applied to account for the temperature difference between the needle tests and the cable operating temperature. The result is a critical stress for cable survival. One can then assume a worst-case scenario that a contaminant could be present at the position of highest design stress of the cable and that contaminant is of sufficient size to cause a failure. A very high permittivity ratio, representative of a metallic contaminant, would be consistent with the worst-case scenario. Based upon the needle tests and demonstration of effective shielding, a tip radius of 10 microns can be assumed to determine the dimension of this ‘critical contaminant’ according to the stress enhancement factor described earlier.

Following the approach described by Ishibashi,

$$E_c > E_{\max} k_T k_m k_f \tag{8}$$

where E_c is the critical failure stress of 300 kV/mm, $E_{\max}$ is the maximum design stress of the cable construction, k_T is a temperature correction factor, k_m is a correction according to the aging model (Ishibashi utilized $n = 15$ from the inverse power law with a cable life expectation of 30 years), and k_f is a geometric stress enhancement factor. With $k_T = 1.2$, $k_m = 2.52$ and an ellipsoidal stress enhancement, Ishibashi estimated that a 500 kV AC cable with inner insulation radius of 19 mm and outer radius of 46 mm would have a largest permissible contaminant of 67 μ (major ellipsoidal axis).

Through the use of the ellipsoidal stress enhancement model previously discussed, this approach can be taken for any proposed cable design where a critical stress enhancement factor can be tolerated, and thereby defines a critical contaminant size (e.g., the major axis length $2a$ where the tip radius R is assumed to be 10 microns using the notations described in Eq. 7). Such an approach has led to industry specifications (as discussed in Sect. 3) to limit protrusions and contaminants, with particular attention to sizes down to 70 μ and even 50 μ, with some specific references to metallic contaminants.

5.6 Dielectric Losses

Dielectric energy dissipation (losses) can result in localized heating of the dielectric if the rate of thermal conductivity out of the dielectric is insufficient. An increased temperature can not only reduce breakdown strength, but will also reduce energetic barriers to enhance dipole and charge carrier mobility and promote further heat generation. Such a condition can lead to ‘thermal runaway’ and result in a thermal failure of the dielectric.

Dielectric power loss in an ac cable (watts per unit length) is proportional to the product of the dielectric constant (real part of the permittivity), the dissipation factor and the square of the applied voltage. Thus, low dielectric constant and dissipation factor are desired and become more important as the application voltage is increased. In the case of a dc cable, the losses associated with the dielectric are due to leakage current, and thus, low conductivity is desired. Leakage current and dc losses will also increase with the application voltage. However, for both ac and dc applications, the efficiency of power transmission is improved at higher voltages, as losses are dominated by Joule heating from the conductor current. The magnitude of power transmitted is the product of the conductor current and the conductor voltage; thus, the conductor current can be reduced in proportion to the increase in application voltage as a means to reduce transmission losses [51].

5.7 Electrical Aging in Wet Environments

Up to this point, the discussion of electrical aging and breakdown has focused on mechanisms which are typically associated with ‘dry-design’ power cables, where the structure of the cable has been designed to resist water penetration into the insulating layer. However, as mentioned in an earlier section, the presence of water has been shown to introduce a different mode of electrical aging which leads to considerable acceleration of the deterioration of the insulation even at relatively low alternating electrical fields (a few kV/mm). This mode of degradation has become known as ‘water treeing’ due to the tree-shaped and bush-shaped structures which form within the insulation and grow predominantly along field lines. An ASTM method for characterization of water treeing resistance was developed, and most distribution cable standards now incorporate wet electrical aging and retention of electrical breakdown strength into material qualifications [52–54].

While some debate may be found regarding the role of electrochemical oxidation of polyethylene in the water treeing mechanism, the demonstration of acceleration of water treeing with increased frequency seems to have generated more consensus in an electromechanical driving force. The permittivity difference between small water clusters and the surrounding polyethylene matrix can create a frequency-dependent electromechanical stress on the polymer matrix. Over time, much like mechanical crack propagation, small water-filled channels can form and continue to provide a conductive path and stress enhancement at the crack tip. Materials designed to resist water treeing have now become well established, either through the use of polymer blends or through the use of water tree retardant additives. Water tree retardant additives (such as polyethylene glycol) are water soluble and can reduce the permittivity difference between additive water solution domains and that of the polyethylene matrix, thereby resulting in a reduced driving force for electromechanical stress. Introduction of a polar polymer (such as an ethylene-alkyl acrylate copolymer) into a blended composition with polyethylene serves to provide a thermodynamically preferred location for any water present within the higher-permittivity polar phase [43, 55, 56].

The introduction of polar species into water tree retardant XLPE compositions results in an increase in the dissipation factor of the compound. Thus, the use of water tree retardant materials in wet designs has been primarily limited to power distribution applications, with some limited extensions into wind farm array cables and wet design high-voltage applications. Recent material developments have been reported which identify water tree retardant compound approaches with substantially reduced dissipation factor at power frequencies, which may result in a greater utility of water tree retardant technology at higher voltages [57–59].

6 Concluding Remarks

Power cables are critical infrastructure component in delivering power or electricity to consumers. The design and specifications vary by region and application. Utilities design the cables and expect the grid to work reliably for a long time. XLPE as an insulation material offers advantages over other polymers. The XLPE materials should be carefully selected based on several criteria, including cleanliness, dielectric properties (high dielectric strength, low dielectric loss), processability and scorch retardance. The molecular structure of polyethylene has an impact on the insulating properties. Rheology and polymer architecture are fine-tuned for this application during the polymerization process by tailoring molecular weight distribution, branching and unsaturation. This provides shear thinning for good processability, high melt strength to avoid flowing due to gravitational forces as the insulation exits the extrusion die and hasn’t yet crosslinked (ensures round cross-section), and good peroxide response during cure. There is ongoing research on molecules that interfere with the electrical breakdown processes to improve the performance of these materials.

References

1. Bernstein B, Thue W (2003) Historical perspectives of electrical cables. In Thue W (ed) Electrical power cable engineering, 2nd ed, Mercel Dekker, New York
2. Black R (1983) The history of electric wires and cables. Peter Peregrinus Ltd.
3. Edison, US Pat 251552, “Street Pipes” Dec 1881
4. Orton H (2013) History of underground power cables. IEEE Electr Insulation Mag 29(4)
5. Bamberger E, Tschimer F (1900) Ueber die Einwirkung von Diazomethan auf b-Arylhydroxylamine. Berichte der Dueschten chemischen Gesellschaft zu Berlin 33:955–959
6. [claims student Hindermann mentioned white substance, later determined to be (-CH2-)x, in his dissertation in Zurich in 1897]
7. Von Pechmann H (1989) Ueber Diazomethan und Nitrosoacylamine. Berichte der Dueschten chemischen Gesellschaft zu Berlin 31:2640–2646
8. Fawcett EW, Gibson RO, Perrin MW, Paton JG, Williams EG (1937) Improvements in or relating to the polymerization of ethylene. British Patent 471590
9. Perrin MW (1953) The story of polythene. Research 6
10. Dobbin C (2017) An industrial chronology of polyethylene. In Spalding M, Chatterjee A (eds) Handbook of industrial polyethylene and technology. Wiley and Sons
11. Pinkney P, Wiley RH (1953) Curing of polyethylenes. US Patent 2628214
12. Gilbert A, Precopio F (1963) Irradiated filler-containing polyethylene. US Patent 3084114
13. Precopio F, Gilbert A (1959) Curable polyethylene comprising a peroxide containing tertiary carbon atoms, and a filler, and process of curing same. US Patent 2888424

14. Precopio F, Gilbert A (1999) The invention of chemically crosslinked polyethylene. IEEE Electr Insulation Mag 15(1)
15. Vostovich J, Bailey C (1960) Extrusion of crosslinked polyethylene and process of coating wire thereby. US Patent 2930083
16. Ward R (1967) Method of making polyethylene insulated electrical conductors. US Patent 3325325
17. US Patent US3225018A to Union Carbide Nathan Zutty, filed in Dec 1961, published in Dec 1965
18. GB1286460A to Dow Corning, Henry George Scott, filed 12-20-1968, published in 8-23-1972
19. A Brief History of EPR Dielectric, EPR Cable Technology Consortium—University of Connecticut; https://eprcable.ims.uconn.edu/epr-cables/; contact Dr. Y. Cao
20. Vahlstrom W (1971) Paper presented at IEEE Conference on Underground Distribution, Detroit, Mich.
21. Lawson RH, Vahlstrom W (197) IEEE Trans PAS 824
22. Lawson J, Vahlstrom Jr W (1973) Investigation of insulation deterioration in 15 kV polyethylene cables removed from service, Part II. IEEE Trans PAS 92:824–831
23. Miyashita T (1971) Deterioration of water-immersed polyethylene coated wire by treeing. IEEE Trans Electr Insul 6:129–135
24. Lawson JH, Vahlstrom W Jr (1973) Investigation of insulation deterioration in 15 kV and 22 kV polyethylene cables removed from service—part II. IEEE Trans PAS 92:824–835
25. Bahder G, Katz C, Lawson JH, Vahlstrom Jr W (1974) Electrical and electrochemical treeing effects in polyethylene and crosslinked polyethylene cables. IEEE Trans PAS 93:977–990
26. Ballard DGH, Burgess AN, Dekoninch JM, Roberts EA (1987) The 'crystallinity' of PVC. Polymer 28:3–9
27. Noel OF, Carley JF (1975) Properties of polypropylene-polyethylene blends. Polym Eng Sci 15(2):117–126
28. Kohan Melvin (1995) Nylon plastics handbook. Carl Hanser Verlag, Munich
29. Hougham GG, Cassidy PE, Johns K, Davidson T (1999) Fluoropolymers 2. Springer
30. Rysselberghe PV (1932) Remarks concerning the Clausius-Mossotti Law. J Phys Chem 36(4):1152–1155
31. Bartnikas R (1983) Dielectric loss in solids. In: Bartnikas R, Eichhorn R (eds) Engineering dielectrics—Volume IIA—Electrical properties of solid insulating materials: molecular structure and electrical behavior. ASTM Publications
32. Bartnikas R (ed) Engineering dielectrics: volume IIB—electrical properties of solid insulating materials: measurement techniques. American Society for Testing and Materials—Special Technical Publication 926
33. Raju G (2003) Dielectrics in electric fields. Marcel Dekker, Inc
34. Dissado LA, Fothergill JC (1992) Electrical degradation and breakdown in polymers. Peter Peregrinus Ltd.
35. Fischer and Nissen (1976) Breakdown behavior of polyethylene. IEEE Trans Electr Insul EI-11(2)
36. Li D et al (2019) Effect of crystallinity of polyethylene with different densities on breakdown strength and conductance property. Materials 12(11):1746
37. Hosier I, Vaughan A, Swingler S (1997) Structure-property relationships in polyethylene blends: the effect of morphology on electrical breakdown strength. J Mater Sci 32:4523
38. Shimizu N et al (1998) Electrical tree initiation. IEEE Trans Dielectrics Electr Insul 5(5):651
39. Ishibashi A et al (1998) A study of treeing phenomena in the development of insulation for 500 kV XLPE cables. IEEE Trans Dielectrics Electr Insul 5(5):695
40. Gross R, Hunt G (1967) Dielectric compositions containing halogenated voltage stabilizing additives. US Patent 3,350,312; Simplex Wire and Cable
41. Heidt L (1970) Solid dielectric polyolefin compositions containing various voltage stabilizers. US Patent 3,522,183; Simplex Wire and Cable
42. Hunt G (1970) Voltage stabilized polyolefin dielectric compositions using liquid-aromatic compounds and voltage stabilizing additives. US Patent 3,542,684; Simplex Wire and Cable

43. Eichhorn R (1983) Treeing in solid organic dielectric materials. In: Bartnikas R, Eichhorn R (eds) Engineering dielectrics—Volume IIA—electrical properties of solid insulating materials: molecular structure and electrical behavior. ASTM Publications
44. Kisin S et al (2009) Polym Degrad Stab 94:171
45. Englund V et al (2009) Polym Degrad Stab 94:823
46. Bostrom J-O et al (2003) Stress enhancement of contaminants in XLPE insulation used for power cables. IEEE Electr Insul Mag 19(4)
47. Bahder G, Eager, GS, Silver DA, Lukac R (1912) Criteria for determining performance in service of crosslinked polythylene insulated power cables. IEEE Trans Power Apparatus Syst 95(5):1552, with reference to a 1912 paper by Larmor and Larmor (Royal Society of London, 1912)
48. N.H. Malik, et al, Electrical Insulation in Power Systems, Marcel Dekker, New York 1998, with reference to H. Bateman, Partial Differential Equations of Mathematical Physics, Cambridge University Press, New York, 1944
49. Bowers AB, Cath PG (1941) The maximum electric field strength for several simple electrode configurations. Phillips Tech Rev 6, #270
50. Orton H, Hartlein R (eds) Long-life XLPE-insulated power cables. Orton Consulting Engineers International, Ltd.
51. Thue W (2003) Electrical power cable engineering, 2nd edn. Marcel Dekker, New York
52. Steennis EF, Kreuger FH (1990) Water treeing in polyethylene cables. IEEE Trans Electr Insul 25:989
53. Pelissou S, Harp R, Bristol R, Densley J, Fletcher C, Katz C, Kuchta F, Kung D, Person T, Smalley M, Smith J (2008) A review of possible methods for defining tree retardant crosslinked polyethylene (TRXLPE). IEEE Electr Insul Mag 24(5):22
54. ASTM D6097 (2016) Standard test method for relative resistance to vented water tree growth in solid dielectric insulating materials. ASTM International
55. US Patent 4305849A (1980) Polyolefin composition containing high molecular weight polyethylene glycol useful for electrical insulation. Nippon Unicar Company
56. Farkas A (1985) Insulation composition for cables. WO 1985005216A1
57. CIGRE TB722 (2018) Recommendations for additional testing for submarine cables from 6 kV (Um = 7.2 kV) up to 60 kV (Um = 72.5 kV). CIGRE Study Committee—WG B1.55
58. Cree S et al (2015) Potential use of new water tree retardant insulation in offshore wind farm array cables. In: Jicable '15, B1.3
59. Caronia P et al (2019) Advancements in TR-XLPE insulation technology to enable use in high-voltage cable applications. In: Jicable'19, B5.1