Chapter 7
Underground Cable Systems

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Glossary

Breakdown	Permanent failure through insulation.
Cable system	Cable with installed accessories.
CCV	Catenary continuous vulcanization extrusion line for extruded dielectrics.
Cross-linked polyethylene (XLPE)	A thermoset unfilled polymer used as electrical insulation in cables.
Diagnostic test	A field test made during the operating life of a cable system. It is intended to determine the presence, likelihood of future failure and, for some tests, locate degraded regions that may cause future cable and accessory failure.
Dielectric loss	An assessment of the electric energy lost per cycle. A poorly performing cable system tends to lose more energy per AC cycle. Measurements can be made for selected voltages or over a period of time at a fixed voltage. The stability of the loss, the variation with voltage and absolute loss are used to estimate the condition. Data can be derived from time-based (if sufficient time is taken) or frequency-based test methods.
Electrical trees	Permanent dendritic growths, consisting of nonsolid or carbonized micro-channels, that can occur at stress enhancements such as protrusions, contaminants, voids,

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	or water trees subjected to electrical stress. The insulation is damaged irreversibly at the site of an electrical tree.
Ethylene propylene rubber (EPR)	A type of thermoset-filled polymer used as electrical insulation in cables and accessories. There are several different formulations of EPR and they have different characteristics. For purposes here, the term also encompasses ethylene propylene diene monomer rubber (EPDM).
Extra high voltage (EHV)	Cable systems within the voltage range 161–500 kV, though more often between 220 kV and 345 kV. Also referred to as transmission class, though usually has higher design stress levels than HV.
Extruded dielectrics	Insulation such as EPR, HMWPE, PE, WTRXLPE, XLPE, etc., applied using an extrusion process.
Filled insulation	Extruded insulations where a filler (carbon black or clay) has been incorporated to modify the inherent properties of the base polymer. This class includes all types of EPR, Vulkene, etc.
High pressure fluid filled (pipe type or HPOF)	paper insulated and installed in trefoil in steel pressure pipes and impregnated with high-pressure nondegradable fluid which is maintained at high pressures by pumping plants – common in USA at HV & EHV.
High voltage (HV)	Cable systems within the voltage range from 46–161 kV, though more often between 66 kV and 138 kV. Also referred to as transmission class, though usually has lower design stress levels than EHV.
Jacket	An extruded outer polymeric covering for cables designed to protect the cable core and the metallic shielding (wires, tapes, or foils).
Joint	A device to join two or more sections of power cable together. A joint includes a connector to secure the cable conductor and a stress controlling/insulating body to manage the electrical stress.
Laminated dielectrics	Insulation formed in layers typically from tapes of either cellulose paper or polypropylene or a combination of the two. Examples are the PILC (paper-insulated lead-covered) and MIND (mass-impregnated non-draining) cable designs.
Mass impregnated non-draining Cable (MIND)	A cable design using paper insulation impregnated with a thick compound such that the compound does not leak out when the lead is breached.
Maximum electrical stress	The highest level of stress also corresponds to the highest probability of instantaneous failure or, equivalently, the highest rate of electrical aging.
MDCV	Mitsubishi Dainichi continuous vulcanization, often called long land die, extrusion line for XLPE, typically for HV & EHV.

Mean or average electrical stress	This is most important if the most serious defects are uniformly located throughout the bulk of the insulation.
Medium voltage (MV)	Cable systems within the voltage range from 6 kV to 46 kV, though more frequently between 15 kV and 35 kV. Also referred to as distribution class.
Metallic shield	A concentric neutral surrounding the cable core. The shield provides (to some degree) mechanical protection, a current return path, and, in some cases, a hermetic seal (essential for impregnated cables).
Minimum electrical stress	This is most important if cable system reliability is determined by the performance of accessories or if the electrical design or installation method of accessories degrades cable performance.
Paper insulated lead covered (PILC)	A cable design using paper insulation impregnated with a fluid and encased in lead to prevent the fluid from leaking out of the insulation.
Partial discharge	A low voltage (mV or μV) signal resulting from the breakdown of gas enclosed in a dielectric cavity. The signals travel down the cable system and may be detected at the end, thereby enabling location.
PE-based	Extruded insulations that do not have an incorporated filler (carbon black or clay). This class includes all types of HMWPE, PE, WTRXLPE, XLPE, etc.
Polyethylene (PE)	A polymer used as electrical insulation in cables.
Power frequency	A substantially sinusoidal waveform of constant amplitude with an alternating frequency in the range of 49–61 Hz.
Self-contained fluid filled (FF or LPOF or PILC)	Paper or paper polypropylene laminated (PPL) insulated with individual metal sheaths and impregnated with a dielectric fluid. Where used these are common in land cable applications. This type of cable is one of the first to be installed in the 1890s.
Shielded cable	A cable in which an insulated conductor is encapsulated in a conducting "cylinder" that is connected to ground.
Space charge	Quasi-permanent injected charge that is trapped within the insulation of a cable system. This charge is sufficient to modify the applied AC and impulse voltage stresses.
Splice	A joint.
Tan δ (TD)	The tangent of the phase angle between the voltage waveform and the resulting current waveform.
Termination	A device that manages the electric stress at the end of a cable circuit, while sealing the cable from the external environment and providing a means to access the cable

	conductor. Devices referred to as elbows or potheads are types of terminations.
VCV	Vertical continuous vulcanization extrusion line for XLPE, typically for HV & EHV
Water tree retardant cross-linked polyethylene (WTRXLPE)	A thermoset polymer used as electrical insulation in cables that is designed to retard water tree growth.
Water trees	Dendritic pattern of electro-oxidation that can occur at stress enhancements such as protrusions, contaminants, or voids in polymeric materials subjected to electrical stress and moisture. Within the water tree the insulation is degraded due to chemical modification in the presence of moisture.

Definition of the Subject

Underground cables have been used from the earliest time as integral parts of the power distribution and transmission system. Compared to their overhead analogues, they have been long regarded as the most critical of components due in part to their high total installed cost, their unique ampacity requirements, and the complexity of their installation. Thus, even from the very first technical papers, the sustainability, through reliability and longevity, has been of paramount importance. This contribution addresses the focus on sustainability today while maintaining a linkage to the lessons that have been already learned.

Introduction

Almost all electric power utilities distribute a portion of the electric energy they sell via underground cable systems. Collectively, these systems form a vast, interlinked, and valuable infrastructure. Estimates for the USA indicate that underground cables represent 15–20% of installed distribution system capacity. This percentage is much closer to 50% in Europe. These cable systems consist of many thousands of miles of cable and hundreds of thousands of accessories installed under city streets, suburban developments, and the countryside. Utilities have a long history of using underground system with some of these cable systems installed as early as the 1890s. Very large quantities of cable circuits were installed in the 1950s–1980s. Today, the size of that infrastructure continues to increase rapidly as the majority of

Table 7.1 Factors encouraging and discouraging the installation of underground cable systems

Encouraging installation of underground cable systems	Discouraging installation of underground cable systems
Public perception of risk	Capital cost – higher for cable systems
Reliability (frequency of outages) – frequency is lower for underground cable systems	Return to service after failure (repair time) – longer repair time
Total operating cost – lower electrical losses & lower repair and maintenance costs	Need for reactive compensation on long lengths AC systems
Public perception of visual impact – lower impact	

newly installed electric distribution lines are placed underground. There are a number of drivers and brakes that control this process and they are shown in Table 7.1.

Cable systems are designed to have a long life with high reliability. However, the useful life is not infinite. These systems age and ultimately reach the end of their reliable service lives. Estimates set the design life of underground cable systems to be in the range of 30–40 years. Today, a large portion of this cable system infrastructure is reaching the end of its design life, and there is evidence that some of this infrastructure is reaching the end of its reliable service life. This is a result of natural aging phenomena as well as the fact that the immature technology used in some early cable systems is decidedly inferior compared to technologies used today. Increasing failure rates of these older systems are now adversely impacting system reliability, and it is readily apparent that action is necessary to manage the consequences of this trend.

Cable System Structure

The name "cables" is given to long current-carrying devices that carry their own insulation and present an earthed outer surface [1]. In this context, overhead lines, for example, are not considered as cables. Power cables have a coaxial structure: Essentially, they comprise a central current-carrying conductor at line voltage, an insulation surrounding the conductor, and an outer conductor at earth potential. AC cables are generally installed as a 3-phase system, and hence, the outer conductor should only carry fault and loss currents. In practice, a more sophisticated construction is adopted. The interfaces between the metal conductors and the insulation (laminated or polymeric) would tend to include contaminants, protrusions, and voids, features that would lead to electrical stress enhancement, accelerated aging, and premature failure [2, 3]. To overcome this, a "semicon" layer, a conductive paper or polymeric composite, is placed at both interfaces. The inner semicon, the insulation, and the outer semicon ensure the interfaces are smooth and contaminant-free. Surrounding this cable are layers to protect the cable during installation/operation and carry the loss/fault currents. These layers also serve to keep out

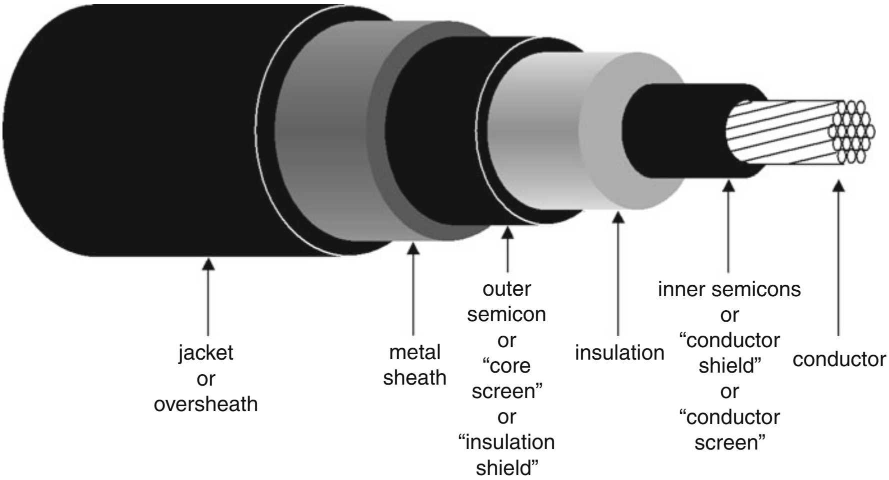

Fig. 7.1 Cut-away section of a typical power cable

Table 7.2 Voltage classes for AC cable systems in selected regions

	MV	HV	EHV
Asia	6.6, 10, 15, 22, 33	66, 90, 110, 132, 154, 161	187, 220, 275, 345, 400, 500, 525
Europe	11, 20, 33	63, 66, 90, 110, 132, 145, 150	220, 275, 380, 400
North America	15, 25, 35, 46	69, 115, 138	220, 230, 345, 500
	Distribution	Transmission	
Nordic	20	90, 132, 145	220, 400

water, which may lead to water treeing in polymer insulations or elevated losses in laminated insulations. A schematic diagram of a power cable is shown in Fig. 7.1.

MV, HV, and EHV Cable Systems

Cable systems that are used for distribution and transmission purposes are generally categorized according to the voltage rating:

- Medium voltage (MV): 6–36 kV
- High voltage (HV): 36–161 kV
- Extra high voltage (EHV): 161–500 kV (or more)

There is no international consistency on the distinction between “distribution” and “transmission.” Which means that although clear in the bulk of the ranges, the edges/transitions get somewhat blurred. Table 7.2 shows the relationship between the voltages and voltage classes of cable systems for selected regions of the world.

Electrical Stresses

The operation of a cable system is very dependent upon the electrical stresses (E) to which it is subjected, for example:

- Dielectric heating $\propto E^2$
- Probability of failure $\propto 1-\exp(E/\alpha)^{\beta}$
- Insulation aging $\propto E^n$

Thus, to understand the many issues associated with sustainability, it requires a firm understanding of the electric stresses in the whole system.

Alternating Current (AC)

The electrical stress within a cable is given by [1].

$$\mathrm{E} = \frac{V}{x \ln\left(\frac{R}{r}\right)} \tag{7.1}$$

where V is the applied voltage, r is the radius over the inner semiconductive screen, R is the diameter over the insulation, and x is the intermediate radius (between r and R) at which the electric stress is to be determined.

The probability of failure depends upon the electrical stress and increases with stress. The effect of an increased stress is most commonly estimated using the Weibull probability function [4]:

$$P_f = 1 - \exp\left\{-\left(\frac{\mathrm{E}}{\alpha}\right)^{\beta}\right\} \tag{7.2}$$

where P_f is the cumulative probability of failure, i.e., the probability that the cable would have failed if the stress is increased to a value E. The two parameters, α and β, are known, respectively, as the characteristic stress and the shape parameter.

Inspection of Eq. 7.1 shows that the electric stress varies with the position within the cable. There are three potentially useful stresses that can be considered:

- Maximum stress at conductor screen
- Mean geometric average stress for the whole insulation
- Minimum stress at the core screen

The decision as to which of these to consider is an important one and is guided by the potential modes of failure:

- Maximum: The highest level of stress also corresponds to the highest probability of instantaneous failure or, equivalently, the highest rate of electrical aging.

Table 7.3 Average stress levels for selected insulations

Type	Stress (kV/mm)	EHV	HV	MV
Fluid filled	Average at core screen	10.0	8	8
	Average at conductor screen	17	14	10.0
EPR	Average at core screen	4	3	2
	Average at conductor screen	8	5	3
XLPE	Average at core screen	5.0	3	2
	Average at conductor screen	11	6	3

This is most important if the most serious cable defects are located on or near the conductor screen.

- Mean: This is most important if the most serious defects are uniformly located throughout the bulk of the insulation.
- Minimum: This is most important if cable system reliability is determined by the performance of accessories or if the electrical design or installation method of accessories degrades cable performance. It is also important if the most serious cable defects are located on or near the core screen.

The range of electrical stresses employed is shown in Table 7.3.

Direct Current (DC)

The stress in AC cables is determined by the capacitance (permittivity) of the structure. However, in DC cable systems, the resistance (resistivity) determines the stress [1, 5]. The permittivity of insulations is essentially stress and temperature independent (within the range of normal use), whereas the resistivity has significant voltage and temperature dependence.

Inspection (Fig. 7.2) shows that in the temperature range (20–60°C), the resistivity can change by 2–3 orders of magnitude. The dependence of the resistivity ρ on stress E and temperature T can be characterized equally well by using the formats of Eqs. 7.3 or 7.4.

$$\rho = \rho_0 \exp(-\alpha T - \beta \mathrm{E}) \tag{7.3}$$

$$\rho = \rho_0 \exp(-\alpha T) \mathrm{E}^{-\gamma} \tag{7.4}$$

where ρ_o is the resistivity at reference temperature, α is the temperature coefficient, and β and γ are the stress coefficients of the insulation.

The practical consequence is that the stresses in a DC cable system are primarily determined by the dimensions, voltage, and the temperature distribution. Thus, the design of DC systems is technologically much more challenging than AC. The most obvious manifestation is the difference (with respect to AC systems) of the location of the maximum stress: In AC systems, this is always located close to the conductor (termed Laplace field in Fig. 7.3); in DC systems, this can move from the conductor

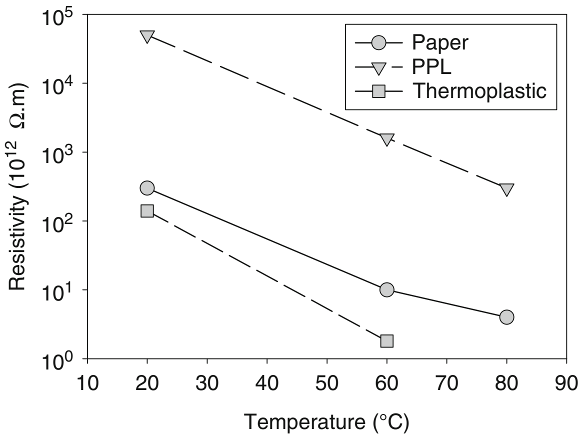

Fig. 7.2 Resistivity of selected insulations at different temperatures

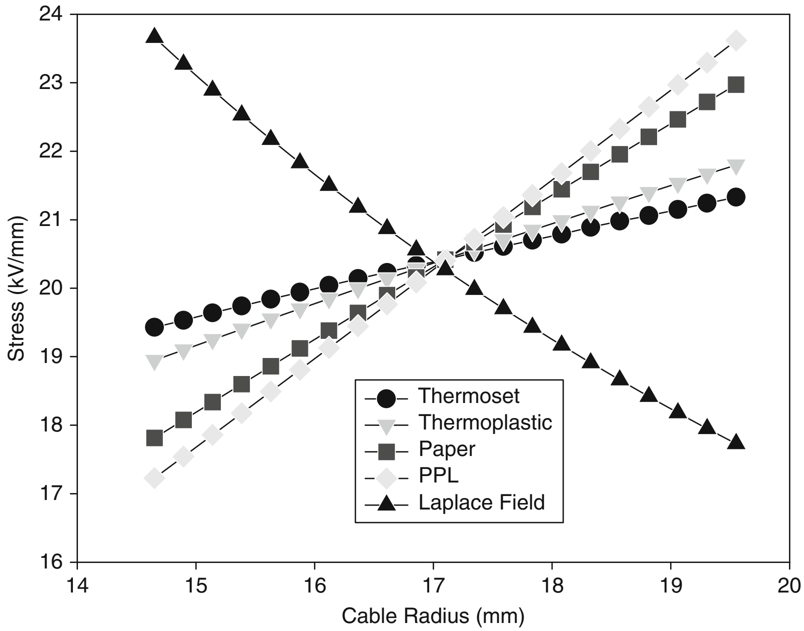

Fig. 7.3 Electrical stress distribution, under load, for a 100 kV DC cable manufactured using different insulants. The power loss *W* is the same for all designs

(no load case) to the outside (highly loaded case) – this is termed stress/temperature inversion.

One of the ways to calculate the electrical stress distribution E_r across the cable insulation at radius *r* can is shown below:

$$E_r = \frac{\delta V (r/r_2)^{\delta-1}}{r_2\left[1-(r_1/r_2)^{\delta}\right]} \tag{7.5}$$

$$\delta = \frac{\alpha W/2\pi\lambda + \beta V/(r_2 - r_1)}{\beta V/(r_2 - r_1) + 1} \tag{7.6}$$

where λ is the thermal conductivity, r_1 is the conductor screen radius, r_2 is the radius over insulation, $W = I^2R$ is the conductor loss, and V is the applied voltage. The α and β parameters are extracted from the resistivity data using Eq. 7.3.

Uses of Cables

Power cables are commonly used in underground or underwater (submarine) connections. Cables are placed at strategic points of the transmission grid to supplement overhead lines or, in some cases, they can form the whole "backbone." Interconnections between networks are particularly well suited to cable solutions [3] for security of supply reasons.

Cables may also be used in other applications rather than just underground or underwater. For example, overhead covered conductors allow smaller phase clearance between the conductors on medium-voltage overhead lines. Objects, particularly tree branches, may touch the lines without tripping or customer outage. This has led to substantial improvements in service reliability (e.g., [5]). In most cases, the aluminum alloy conductor is covered with black UV-resistant cross-linked polyethylene and filled with grease, to provide corrosion protection and longitudinal water-tightness. Arcing guides are applied at insulator tops, to protect the line from arcing damage. Another application is the "Powerformer" [6] and the related "motorformer." These new generators are able to supply electricity directly to the high voltage grid without the need for a step-up transformer. It is suitable for power generation at output voltages of several 100 kV. One example of this is the Troll motorformer project on an natural gas rig in the North Sea. The new concept is based on circular conductors for the stator winding, and it is implemented by using proven high-voltage cable technology. Thus, the upper limit for the output voltage from the generator is only set by that of the cable.

AC and DC Transmission

Cable systems are used in both alternating current (AC) and direct current (DC) schemes. The cable designs used in each case are outwardly very similar and have many identical design elements. However, the detailed engineering and the

Table 7.4 HVDC projects using extruded cable systems

Project	Type of Project	Power MVA	Voltage rating KV	Cable length km	In service Year
Gotland/SE	S	60	80	140	1999
Directlink/AU	TL	180	84	390	2000
Tjæreborg/DK	WIND	8	10	8	2000
Cross Sound/US	S	330	150	82	2002
Troll/NO	OFF	80	60	70	2004
Estlink/FI	S	350	150	105	2006
Valhalla/NO	OFF	78	150	292	2009
NordEon/DE	WIND	400	150	390	2009
Transbay/US	S	400	200	95	2010

S Subsea Interconnection, *OFF* Offshore Power Supply, *WIND* Windpower Delivery to Shore, *TL* Trading Link

materials used are very different. AC is the globally preferred means of transferring electric power. This form of transfer makes it straightforward to generate electricity and to transform voltages up and down. This means of transfer accounts for more than 98% of the global power infrastructure.

In long-distance transmission schemes, especially those that are of interest in the future such as windfarms or solar plants, there are very significant advantages in using DC over AC. System instabilities caused by connecting regions with slightly different AC phases and frequencies are obviated. Capacitive charging current implies that there is a maximum useful length of AC cables without the use of shunt reactors. DC cables are therefore particularly useful for long-distance submarine connections. Furthermore, the lack of electromagnetic effects under DC conditions eliminates the skin effect in which the conductor resistance can rise by up to 20% at 50 Hz. The drawbacks for a DC solution are that the terminal equipment for AC/DC conversion is seen as more costly and less efficient than AC transformers. (Reviews on AC/DC power transmission are contained in [7].) Thus, the system must be sufficiently long to be economically viable. In addition, the control of the electrical stress in a DC cable insulation is also much more difficult due to thermally induced stress inversions and stress modifications due to trapped space charge. The space charge issues are particularly onerous at interfaces, such as those that occur at accessories (joints and terminations).

Before 2000, cables using lapped/impregnated (oil or compound) insulations were almost exclusively used for DC transmission up to 500 kV and very long distance. Even today this technology is preferred for the highest voltages (EHVDC) and distances. However, the recent development in the HVDC and lower power range has seen the symbiotic development of cable systems and converter technologies. The pace of this development has been quite rapid such that the current installed lengths (not at similar voltages) of paper and extruded cables are approximately equal at 22,500 km. A selection of HVDC projects using extruded cables is shown in Table 7.4.

Cable Types

There are, in general, four types of underground power cable technologies in use today:

- *Polymeric*: Cross-linked polyethylene (XLPE), water tree retardant cross-linked polyethylene (WTRXLPE), or ethylene propylene rubber (EPR).
- *Self-contained fluid filled (FF or LPOF or PILC)*: Paper or paper polypropylene laminated (PPL) insulated with individual metal sheaths and impregnated with a dielectric fluid. Where used these are common in land cable applications. This type of cable is one of the first to be installed in the 1890s.
- *Mass impregnated non-draining (MIND or solid)*: Paper insulated with individual metal sheaths and impregnated with an extremely high viscosity poly-butene compound that does not flow at working temperatures – common at MV and submarine HVDC.
- *High pressure fluid filled (Pipe Type or HPOF)*: Paper insulated and installed in trefoil in steel pressure pipes and impregnated with high pressure nondegradable fluid which is maintained at high pressures by pumping plants – common in USA at HV & EHV.

The typical electrical stresses employed in cables are shown in Table 7.3.

Up until the mid-1980s, paper-insulated cables (PILC, MIND & LPOF) were the system of choice at medium and high voltages. However, improvements in polymeric cables and accessories plus environmental concerns with the impregnation (dielectric fluid and the associated lead sheaths) have led to a significant reduction in the use of paper cables for land applications. In particular, at MV, there has been a strong preference for XLPE & WTRXLPE cables over EPR (except in Italy and USA). XLPE/WTRXLPE and EPR have emerged as the favored polymeric insulations through the 90°C continuous operating temperature that can be achieved when they are used. This temperature matches that which can be attained when fluid-filled lapped insulations (paper and PPL) are used. In contrast, LDPE and HDPE are limited to operating temperatures of 70°C and 80°C, respectively. As a consequence, these insulations have fallen into disuse.

Tables 7.5 and 7.6 identify some of the main advantages of the respective technologies at distribution and transmission voltages.

The situation today is:

- Almost all new HV and EHV systems that are being installed are new build/expansion.
- The majority of HV cables, *already installed* within the existing system, are insulated with paper (83% paper and 17% polymeric).
- There is very little replacement of existing paper cables: Most of installed capacity is based on paper.
- Most HV transmission is by overhead lines (OHLs).
- HV cables are replacing OHLs in environmentally sensitive areas but there is limited impact (globally) on new OHLs.

Table 7.5 Advantages (+) and disadvantages (−) of MV cable insulations

XLPE 11–46 kV	EPR 11–46 kV	WTRXLPE 11–46 kV	Paper 11 to 46 kV (PILC and MIND technologies)
+ No risk of oil leakage	+ No risk of oil leakage	+ No risk of oil leakage	– Oil leakage in PILC technology 0 Reduced compound leakage in MIND technology
+ Very low dielectric losses	0 Medium dielectric losses	+ Low dielectric losses	– High dielectric losses
+ Simple accessory designs which require competent workmanship	+ Simple accessory designs which require competent workmanship	+ Simple accessory designs which require competent workmanship	0 Simple/robust accessories which require high level of workmanship – installation skills disappearing with aging of the workforce
– Likely to suffer from water trees if no metal sheath	0 Less likely to suffer from water trees if no metal sheath	0 Less likely to suffer from water trees if no metal sheath	+ Metal sheath required to contain fluid, thus water is excluded
0 Standard Size	0 Standard Size Reduced size available in special designs	0 Standard Size	+ Small size – higher design stresses – important for installation in ducts

Table 7.6 Advantages (+) and disadvantages (−) of HV & EHV cable insulations

XLPE 66–500 kV	EPR 66–138 kV	Paper 66–500 kV (low-pressure and high-pressure technologies)
+ No risk of oil leakage	+ No risk of oil leakage	0 Oil leakage is a concern
+ Simple design	+ Simple design	– Complicated design – High maintenance burden
+ Very low dielectric losses	0 Medium dielectric losses	0 Medium dielectric losses
+ Acceptable fire performance	+ Acceptable fire performance	– Fire performance in tunnel and substation applications is a concern due to the copious supply of flammable oil
+ Simple accessory designs which require high level of workmanship	+ Simple accessory designs which require high level of workmanship	0 Simple accessories which require high level of workmanship – installation skills disappearing with aging of the workforce
0 Growing track record	– Limited track record	+ Extensive track record
– Likely to suffer from water trees if no metal sheath	– Likely to suffer from water trees if no metal sheath	+ Metal sheath required to contain fluid, thus water is excluded
– Large size	– Large size	+ Small size – higher design stresses

- XLPE cables make up 80–90% of the HV cable capacity *presently being installed.*

  The reasons that there has been little replacement of paper cables are:

- Paper cables continue to operate reliably.
- Operating temperatures have been considerably below the temperature limits
- The designs of XLPE cables are too large to fit existing rights of way or pipes that have been designed for paper cables. This is of special importance in the USA where there are many paper cables and small tight ducts. In this area, the key task is to develop polymeric cables designs that are flexible, small (i.e., working at high stresses), and easy to join as it is essential to use the existing pipes/ducts. Present designs address these issues, and now, cables exist that match the size and performance of paper cables [8, 9].

Components of the Cable

Conductor

Conductors in the USA tend to be based on the American wire gauge (AWG), but, in the rest of the world, are based on IEC228 and are therefore described using the metric convention. Stranded conductors have generally comprised concentric layers, but, in order to make them smoother and more compact, they are often specially shaped in rolling mills nowadays. When operating at high voltages and currents, the AC current is preferentially carried more in the outer than in the inner conductors (the skin effect). In addition, the electromagnetic fields induce eddy currents (proximity effect). These effects tend to increase the conductor resistance under AC above that which is seen under DC. The AC/DC ratio ($R_{AC/DC}$) can be as large as 1.15. This increased resistance serves to increase the Joule heating losses within the conductor and increases the temperature of the cable. Thus, special “Milliken” conductors may be used for large conductor designs to reduce the AC/DC ratio.

Conductors are virtually all made from either copper or aluminum. Copper has the advantage of being more conductive, and therefore, requires less material to carry a given current. Copper conductors, therefore, have the advantage of being small. However, the cost of aluminum, although variable, is lower than that of copper, and even though it has a lower conductivity, it is often used as the conductor. An additional advantage of aluminum over copper is that the conductors are lower in weight even though more volume of material is used. At MV, aluminum is preferred whereas, at HV and EHV, the smaller size of copper provides the greatest advantage.

Semicon

Semiconductive screening materials are based on carbon black, manufactured by the complete and controlled combustion of hydrocarbons. The carbon conducting medium is dispersed within a paper or polymer matrix depending upon the type of cable involved. In early designs of polymeric cable, paper tapes or painted carbon screens were used. These displayed extremely poor service performance as they were seen to dramatically accelerate the growth of water trees. In these cases, failures occurred many years short of the anticipated design life. Current designs of polymeric cables (XLPE, WTRXLPE, or EPR) use extruded polymeric materials to construct the semiconducting screen. Optimal performance is obtained when the screens are coextruded with the insulation in a closed “true triple” extrusion head.

The concentration of carbon black, in both paper and polymeric screens, needs to be sufficiently high to ensure an adequate and consistent conductivity. The incorporation must be optimized to provide a smooth interface between the conducting and insulating portions of the cable. The smooth surface is important as it decreases the occurrence of regions of high electrical stress [10]. To provide the correct balance of these properties, it is essential that both the carbon black and polymer matrix be well engineered.

The same care needs to be paid to the manufacture of the matrix materials (paper or polymer) for semicons as for the insulation. In the case of extruded screens, the chemical nature of the polymers is subtly different from those used for the insulations because of the need to incorporate the carbon black. The carbon black and other essential additives (excluding cross-linking package) are compounded into the matrix. The conveying and compounding machinery used are designed to maintain the structure of the carbon black within a homogeneous mix. Before the addition of the cross-linking package, filtration may be applied to further assure the smoothness of the material, to a higher standard than that provided by the compounding process.

The smoothness of the extruded cable screens is assured by extruding a sample of the complete material in the form of the tape. The tape is optically examined for the presence of pips or protrusions. Once detected, the height and width of these features are estimated, thereby enabling width-segregated concentrations to be determined. When using such a system, care needs to be exercised when examining the present generation of extremely smooth (low feature concentration) screens, as the area of tape examined needs to match the likely number of detected features: Smooth screens require larger areas of examination.

Insulation

It seems clear that, globally, XLPE or its WTRXLPE variants are the most commonly used cable insulations currently being installed. Insulating XLPE compounds need to fulfill a number of requirements. They should act as thermoplastic materials within the extruder and crosshead. They should cross-link efficiently with the application of high temperatures and pressures within the vulcanization tube. They should be immune to thermal degradation throughout the cable manufacture process and operation at the maximum cable temperature for the life of the system. They must display an extremely low occurrence of the features that can enhance the applied electrical stress and thereby lead to premature failure. To deliver these requirements, it is essential that the greatest care is paid to the design and manufacture of the polymer and the engineering of the appropriate cross-linking and stabilizing packages.

The manufacturing technology employed for XLPE compounds to be used for power applications needs to ensure the highest level of cleanliness at all points of the production chain. The sequence comprises three main parts: base polymer manufacture, addition of a stabilizing package, and addition of the cross-linking package. The most common route for cross-linking in cables (XLPE, WTRXLPE, and EPR) is peroxide cure – thermal degradation of an organic peroxide after extrusion causes the formation of cross-links between the molten polymer chains.

Cleanliness

The cleanliness of XLPE and WTRXLPE insulation materials may be assessed by converting a representative sample of the polymer into a transparent tape and then establishing the concentration of any inhomogeneities. This is not possible for monosil as the chemistry occurs immediately prior to the cable extrusion. The inhomogeneities are detected by identifying variations in the transmission of light through the tape. To gain the required level of consistency and sensitivity, the tape is inspected by an automated optical system.

Metal Sheath

For many years, lead or lead alloys were the main materials used for the metal sheath layer. This is principally because the low melting temperature allows the lead to be extruded at a temperature of approximately 200°C over the polymeric cable. The main disadvantages of lead are its high density (11,400 kgm^{-3}) leading to a heavy product; environmental concerns; and the tendency to creep, flow, or embrittle under cyclic temperature loadings. This latter effect has led to a number of cases where the sheath ruptured. There are also environmental concerns relating to the use of lead. Its use may become restricted by European Union (EU) directives. In 2000, the EU Commission officially adopted the waste electrical and electronic equipment (WEEE) and reduction of hazardous substances (ROHS) proposals. The ROHS proposals required substitution of lead and various other heavy metals from 2008. To address these problems a number of materials have been used.

- *Extruded aluminum*: This has excellent mechanical performance but requires a large bending radius and can be difficult to manufacture since it requires corrugations. It can be heavy.
- *Aluminum foil*: This is light and easy to manufacture but small thicknesses (0.2–0.5 mm) do not give mechanical protection; the strength comes from the

polymer oversheath. It relies on adhesive to make a watertight seal, and it can suffer from corrosion.

- *Copper foil*: This is light, easy to manufacture but not as flexible as aluminum foil. It also relies on adhesive to make a watertight seal.
- *Welded copper*: This is strong, robust, and capable of carrying significant current but difficult to manufacture since it requires corrugation and it is difficult to ensure perfect longitudinal welds in practical situations.
- *Welded stainless steel*: This is strong, robust, and capable of carrying significant current but has similar manufacturing difficulties to welded copper.

Oversheath (Jacket)

In addition to the meticulous attention that must be paid to the insulation system, care also needs to be taken with the oversheath layer. One of the earliest lessons that was learned from MIND and PILC cables (where a lead sheath is employed) is that installation damage and corrosion can compromise the metallic sheath [11, 12]. Once sheath integrity is lost, water may enter and impregnant leak out. In these cases failures in service occurred quite rapidly. These issues were soon resolved on neoprene tape or extruded oversheaths were used. When extruded cables were introduced in the mid-1960s, it was believed that there was no longer a need for an oversheath as the insulating polymers were themselves waterproof. However, the phenomena of water treeing soon showed that a good-quality cable jacket was extremely valuable even at the low electrical stresses prevalent at MV.

The vast majority of HV and EHV XLPE cables are of the “dry design” type, which means that a metal barrier is included. The purpose of the metal barrier is to protect the core within from mechanical damage, carry fault and loss currents, and to exclude water from the construction. (The electrical aging rate is significantly higher in the presence of moisture.) The metal barrier is a key part of the cable design and much care needs to be taken as this significantly affects how a cable system may be installed in practice. In a similar way to that at MV, the metal layer is itself protected by a polymeric oversheath. Due to the critical performance needed from the oversheath, there are a number of properties that are required: good abrasion resistance, good processing, good barrier properties, and good stress crack resistance. Experience has shown that the material with the best composite performance is an oversheath that is based on polyethylene.

Cable Manufacture

Stages of Cable Manufacture

The stages in cable manufacture may be summarized as:

1. *Conductor manufacture*: This involves
   - *Wire drawing* to reduce the diameter to that required
   - *Stranding* in which many wire strands and tapes are assembled
   - *Laying up*: the assembly of noncircular (Milliken) segments into a quasi-circular construction
2. *Core manufacture*: This involves
   Paper (LPOF, MIND, PILC) cables
   - *Lapping* in which the core of the cable is formed by wrapping semiconducting and insulation tapes around the conductor with prescribed tensions and paper tape overlaps
   - *Laying up (triplexing)* for three core cables
   - *Drying* which improves the dielectric properties of the cable core and is carried out at elevated temperatures and under vacuum

   Polymer (XLPE, WTRXLPE, and EPR) cables
   - *Triple extrusion* in which the core of the cable is formed comprising the inner semicon, insulation, and outer semicon.
   - *Cross-linking* which is carried out directly after extrusion (peroxide cure).
   - *Degassing* in which peroxide cross-linking by-products are removed by heating offline. The diffusion time depends upon temperature and insulation thickness.
3. *Cable manufacture*: This involves
   Paper (LPOF, MIND, PILC) cables
   - *Impregnation* where the dry paper tapes are impregnated at elevated temperatures with dry/degassed dielectric fluid
   - *Metal sheathing*: the application of a metal impregnant enclosure
   - *Oversheathing*: the application of high strength extruded polymeric oversheath (jacket)
   - *Armouring*: the application of high strength metal components (steel) to protect the cables; essential for submarine cables
   - *Routine testing*: voltage withstand and ionization factor tests

   Polymer (XLPE, WTRXLPE, and EPR) cables
   - *Core taping* during which cushioning, protection, and water exclusion layers inner semicon, insulation, and outer semicon are applied over the extruded core
   - *Metal sheathing*: the application of a metal moisture and protection layer
   - *Oversheathing*: the application of high strength extruded polymeric oversheath (jacket)
   - *Armouring*: the application of high strength metal components (steel) to protect the cables; essential for submarine cables
   - *Routine testing*: voltage withstand and partial discharge tests

Table 7.7 General correlation of extrusion equipment with extruded insulation materials

	MV			HV			EHV		
	EPR	WTR XLPE	XLPE	EPR	WTR XLPE	XLPE	EPR	WTR XLPE	XLPE
Catenary vulcanization 	X	X	X	X	–	X	–	–	X
Vertical vulcanization 	–	–	–	–	–	X	–	–	X
Horizontal vulcanization 	–	–	–	–	–	X	–	–	X

Methods of Core Manufacture for Extruded Cables

All of the production processes will be common to all methods of manufacture, with the exception of the extrusion process where there are three types of peroxide cross-linking methods. (Cross-linking is often referred to as vulcanization or curing.)

- *VCV*: Vertical continuous vulcanization
- *CCV*: Catenary continuous vulcanization
- *MDCV*: Mitsubishi Dainichi continuous vulcanization, often called long land die

In all of these processes, the three layers of the cable core are extruded around the conductor. This un-cross-linked core then passes directly into the curing tube; this is where differences in the processes become apparent. In the moisture cure approach, which takes place offline after extrusion, the manufacturing process is considerably simplified as the length of the tube following extrusion only has to be long enough for the thermoplastic core to cool sufficiently to prevent distortion.

The general relationship between manufacturing method, the insulation technologies, and voltage classes is shown in Table 7.7.

Failure Processes

Power cable systems are designed to be high-reliability products. The failure of a major power cable is likely to have a considerable effect on the power transmission grid and may take several days/weeks to repair. If it is under the sea, it may

Table 7.8 System performance for a 20kV XLPE ([13])

Class	Fault rate (#/year/100 cct km)
Total system	2.0
Third party damage	1.0
Accessories	0.9
Cable	0.1

take months/years to repair and cost well in excess of $3 million (€3 million). Cables have a good service history. The majority of cable failures are caused by external influences such as road diggers or ship anchors. Cable system failures may also occur at joints and terminations.

A study of MV cable systems in France [13] has shown that the failure rate for paper cables is 3.5 failures per 100 cable km per year which compares with a rate of 2 failures per 100 cable km per year for XLPE cables. The failure rate for XLPE has been classified in Table 7.8. This analysis shows that the XLPE cables form the most reliable component of the cable system. Further inspection would suggest that the XLPE cable system is 2.5 times more reliable than the paper system when third party damage is excluded. (It is assumed that a paper cable is as likely to get dug up as an XLPE one!) This estimate may well overstate the case and illustrates one of the major problems of evaluating field failure statistics, namely, the differing ages of the populations. XLPE data are based on a population which is 15 years old whereas the paper data are based on a population that is 30–40 years old; thus, higher failure rates of the paper system are expected since it contains older devices; this would be quite independent of the intrinsic reliabilities of the systems.

The service performance of cable system accessories (joints and terminations) depends upon six essential elements:

- Connector design
- Joint/termination body design
- Installation methods
- Installation quality
- Operating conditions

A more recent study in the USA [11] estimated a median failure rate of 3.5 failures per 100 cct miles per year. Figure 7.4 shows an estimate of how these failures are disbursed by the sources of failure. At first sight, these figures seem to be quite different to the EDF study; however, it should be recognized that there will be considerable variation due to utility and geographical location. For example, the average percentage of failures ascribed to splices is 37%; however, this can range from 5% to 80% depending upon utility. Nevertheless, these studies both show that it is important to consider the cable system as a whole entity.

In general, the causes of insulation breakdown will include the causes listed below. Table 7.9 shows how the types of defects may be related to the failure modes for the different voltage classes of cables. Many of these defects are shown schematically in Fig. 7.5.

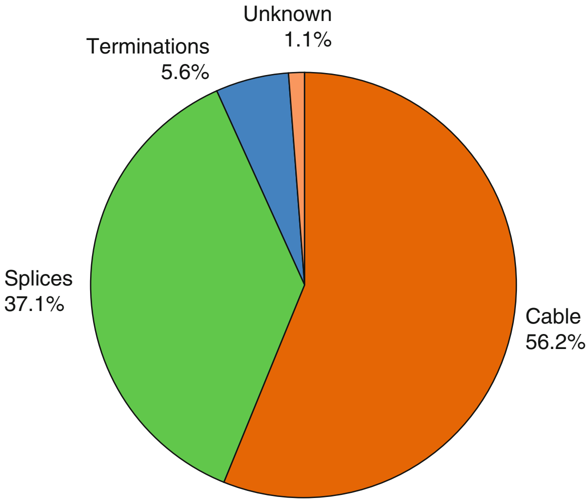

Fig. 7.4 Estimated dispersion of North American MV cable system failures by equipment type

Table 7.9 Role, in general terms, of defects in cable failure modes

Cause of failure	MV	HV	EHV
Extrinsic defects *Contaminants* *Delaminations* *Protrusions* *Shield interruptions* *Voids/cracks*	Accelerants for water treeing	Major source of failure Accelerants for electrical treeing	Major source of failure
Water treeing *Bowtie* *Vented – partial* *Vented bridging*	Major source of failure for extruded	Can be an issue if robust metallic water barriers are not used	Rarely an issue due to the use of robust metallic water barriers
Water ingress	Major source of failure for laminar	Major source of failure for laminar	Rarely an issue due to the use of robust metallic water barriers
Thermoelectric aging	Rarely an issue due to the low temperatures and stresses of operation	Major source of failure accelerated by extrinsic defects	Major source of failure accelerated by extrinsic defects

- Extrinsic defects (contaminants, protrusions, or voids) caused during manufacture or installation. These would normally lead to electrical treeing or direct breakdown soon after production of the void and cable energization.
- Water treeing ("wet aging") caused by water leakage through the sheath or inappropriate design or deployment of a cable without a water barrier. Water trees lead to a weakening of the insulation and electrical treeing or direct breakdown.

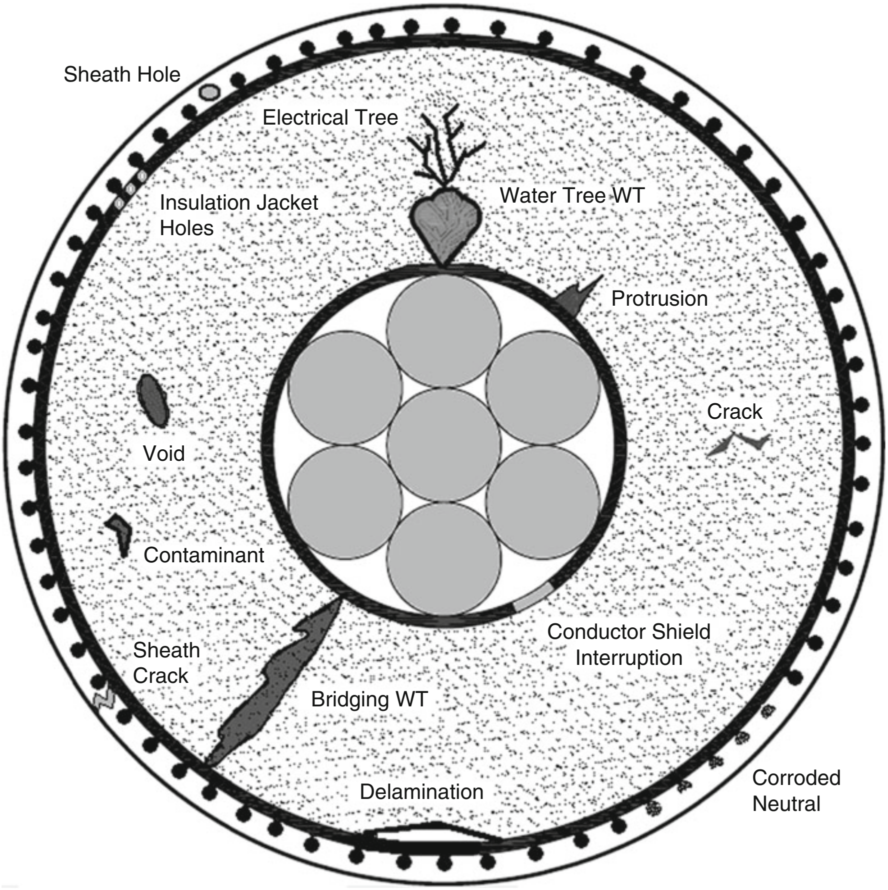

Fig. 7.5 Typical power cable defects

- Water ingress caused by failure of the metal water barriers. Water increases the dielectric loss and thereby leads to local overheating. Failure proceeds by thermal runaway in a region with compromised local breakdown strength.
- Thermoelectric aging: The combination of the electric field, acting synergistically with a raised temperature, causes the insulation to weaken over time and for breakdown to occur eventually. This process may not always be significant within the lifetime of a well-designed cable.

Extrinsic Defects

The efforts made have already been described, from the earliest times, by cable manufacturers to exclude and detect contaminants, protrusions, and voids (CPVs) in their products. Contaminants within the bulk of the insulation and protrusions into the insulation from the semicon cause field intensifications that lead to premature failure of the polymer.

The degree of aging follows the empirical Inverse Power Law relationship with the electric stress ($\propto E^n$) [2, 3, 12, 14, 15].

Contaminants and Protrusions

Many studies [2, 3, 5, 11, 12, 14–18] have shown the degradation caused by large metallic contaminants. Generally contaminants and protrusion type defects reduce the characteristic strengths of insulators; furthermore, the increasing size of contaminants changes the statistical nature of the failures, making them less scattered or more certain.

The effects may be explained by the fact that metallic contaminants increase the electric stress within their immediate locality such that the local electric stress is higher than the breakdown strength of the insulator. This effect is best described in terms of a stress enhancement factor that acts as a multiplier for the Laplacian stress (i.e., the geometrically calculated stress). It is interesting to note that it is possible to get large stress enhancements at sharp metallic contaminants but that the magnitude of the enhancement falls dramatically with distance from the tip; for a 5-μm radius, the field falls by 50% within 1.5 radii of the tip [10]. Thus, the calculated stress enhancements should be viewed as providing the upper limits of any assessment and it is quite challenging to relate them directly to the likelihood of failure.

The electrical stress enhancements are not only based on the size and concentration but they have a significant influence from the nature (conducting, insulating, high permittivity), the shape (sharp or blunt), and the way that they are incorporated into the matrix. The effect of the shape of contaminants has been assessed [18] using XLPE cups with a Rogowski profile. It was shown that contaminants with irregular surfaces reduced the AC ramp breakdown strength by a greater degree than those with smooth surfaces.

The local stress enhancement experienced within an insulator will have contributions from the size of the contaminants, their concentration, and the nature (conducting or high permittivity) of the contaminants. This is shown in Eq. 7.7:

$$\eta = 1 - \frac{1}{\alpha}\left(0.5 \ \ln\frac{\lambda + 1}{\lambda - 1} - \frac{\lambda}{\lambda^2 - 1}\right) \tag{7.7}$$

where:

$$\alpha = 0.5 \ \ln\frac{\lambda + 1}{\lambda - 1} - \frac{1}{\lambda} + \frac{1}{(k-1)\lambda\left(\lambda^2 - 1\right)}$$

$$k = \frac{\varepsilon_2}{\varepsilon_1} \qquad \lambda = \frac{1}{\sqrt{1 - \frac{r}{a}}}$$

η = stress enhancement factor,
r = radius of the ellipse,
$2a$ = length of the ellipse,
ε_1 = permittivity of the matrix, and
ε_2 = permittivity of the defect.

Voids

Voids are likely to lead to breakdown *if* discharges occur inside them. These discharges are known as "partial discharges" since they are not, in themselves, a complete breakdown or "full discharge." The least problematic (and perhaps the least likely) shaped void is the sphere. The field inside an air-filled, sphere-shaped void is higher than the field in the insulation by a factor equal to the relative permittivity of the solid. For other shaped voids, the field in the void will be higher than this. For example, a void inside XLPE (relative permittivity = 2.3) will have a field inside it of at least 2.3 times that of the field in the XLPE itself. The criterion for a discharge in a void is that the void field must exceed the threshold described by the Paschen curve (see [12] for example); this is dependent on the size of the void and the gas pressure within it. The Paschen field has a minimum for air at atmospheric pressure for a void diameter of 7.6 μm. The breakdown voltage at this diameter is 327 V. This equates to a void field (ignoring the nonlinear effects) of 43 kV/mm or an applied field of 19 kV/mm within the XLPE. Below this void size, the Paschen field increases rapidly; for example, a 2-μm void would require an applied field of approximately 150 kV/mm to cause discharging. It is clear then that voids of diameter exceeding a few microns are likely to allow severe electrical damage to occur.

Partial Discharges and Electrical Treeing

In an electrical discharge, electrons are accelerated by the electric field such that their kinetic energy may exceed several electron-volts. With such energies, collisions with gas molecules may cause further electrons to be released, thus strengthening the discharge or they may cause electroluminescence and the release of energetic photons. The surface of the void is therefore likely to be bombarded by particles (photons or electrons) with sufficient energy to break chemical bonds and weaken the material. In the case of sharp protrusions or contaminants, which give rise to high local electric fields, electrons may be emitted and very quickly acquire the kinetic energy required to cause permanent damage to the insulation. Electrons may accumulate – i.e., they may be trapped – around such defects and cause a further increase in local electric fields. Mechanical stress, which may already be increased due to the modulus and thermal expansion coefficient differences between the host materials and the CPVs, may be further enhanced by electromechanically induced stress. These effects, catalyzed by CPVs in an electric field may lead directly to a breakdown path, but are more likely to lead first to the formation of an electrical tree.

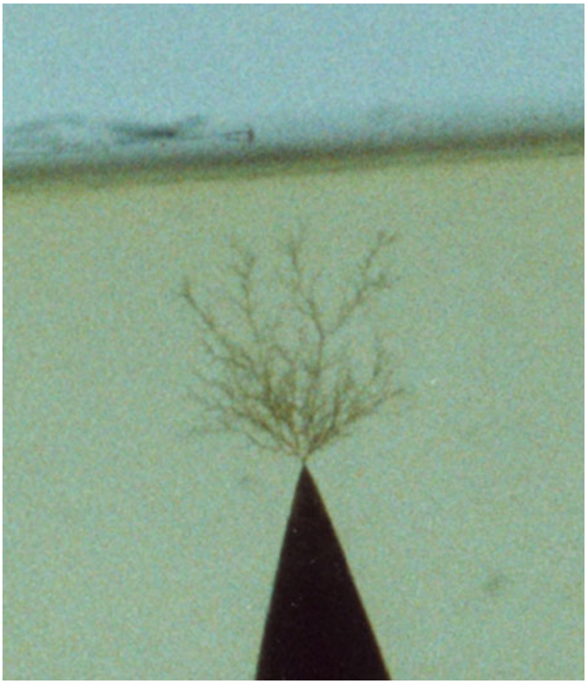

Fig. 7.6 An electrical tree grown in epoxy resin

An electrical tree is shown in Fig. 7.6. For the sake of clarity, this has been grown in a translucent epoxy resin from a needle acting as a protrusion. A breakdown path can be seen to be growing back through the electrical tree from the plane counter-electrode. Electrical trees have a branched channel structure roughly oriented along the field lines. Typically, the diameters of the channels are 1–20 μm, and typically, each channel is 5–25 μm long before it branches. There is considerable evidence that the branching is determined by the local electric field, which is grossly distorted by trapped electrons emanating from the discharges within the tree. There is a considerable body of work on this subject (e.g., [12]). Trees tend to grow more directly across the insulation if they are spindly, so-called branch trees. The other type of tree, the "bush" tree, uses the energy to produce a lot more dense local treeing and, therefore, tends to take longer to bridge the insulation. Because branch trees occur at *lower* voltages, there is a non-monotonic region between branch and bush growth in which failure occurs more quickly at lower voltages. Trees grown from larger voids can be clearly distinguished from those due to protrusions; it is noticeable that the fields must cause the voids to discharge before the trees initiate. After an initial period in which the tree grows fast, the rate of growth decreases. Finally, as the tree approaches the counter-electrode, a rapid runaway process ensues.

Although the electric tree processes are now quite well understood, apparently little can be done to prevent electrical tree propagation in polymeric insulation once it has started. It is thought that electrical trees take relatively little time to grow and cause breakdown in cables, perhaps a few minutes to a few months. Once an electrical tree has been initiated, the cable can be considered to be "terminally ill." It is therefore vital to prevent the inclusion of CPVs during cable manufacture and installation. The triple extrusion continuous vulcanization techniques and appropriate cable protection and deployment techniques appear to have been successful in this regard, and cables rarely suffer from these problems. There are more likely to be problems at joints or terminations where high field stresses may inadvertently be introduced or if water trees, described in the following section, are allowed to grow.

Interaction Between Moisture and Temperature

One of the effects of water entering an insulation is that it tends to increase the permittivity and loss of the insulation [1, 19, 20]. The energy lost per cycle within an insulation is proportional to both the permittivity and the loss. Thus, at a given electrical stress, the increasing energy loss due to the presence of water will lead to an elevated temperature. If this temperature becomes too high, other mechanisms come into play and there is a thermal runaway to failure.

Although this happens in principle in all insulations, and may be very important at the high stresses of HV & EHV systems, this is most commonly observed in paper-insulated MV cables. The sensitivity of these cables is due to the fact that the dielectric losses are initially much higher and the paper and oils have a higher propensity to absorb water. Some basic measurements were made by Blodgett [19] who showed that the loss in paper insulations increased with both temperature and moisture. These data can be used within cable system rating models to estimate the thermal equilibrium for selected temperatures and moisture contents. The results are shown in Fig. 7.7 which shows the increment above the base-case temperature in the form of a contour-plot for selected moisture contents and temperatures. Inspection shows that significant temperature rises can be expected for quite reasonable moisture contents. A separate study has shown that cables removed from service but not failed might be expected to have a median moisture content of 1%, but cables that failed had moistures in excess of 3%. Thus, the thermal runaway mechanism seems to be a reasonable explanation of the observed phenomena. Moreover, the calculations show the difficulty of setting wide-reaching criteria; a common empirically determined maximum permitted moisture level is 3%. However, the impact of this level of moisture is quite different for different cables and temperatures: 3°C, 7.5°C, 14°C for 15 kV/90°C, 35 kV/90°C, and 35 kV/105°C, respectively.

Wet Aging: Water Trees

In the early days of polymer-insulated cables, it was assumed that the polymers would be essentially immune to the deleterious effects of water that were well

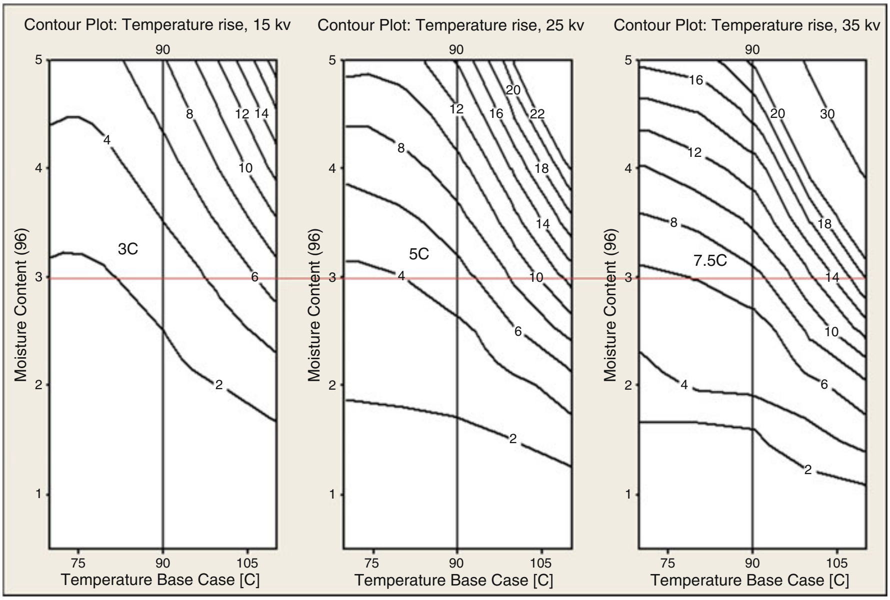

Fig. 7.7 Contour plot of temperatures increment (°C) above base-case temperature for selected base temperatures and moisture content. The calculations have been made for three difference cable voltages

known in paper cables. Consequently, the first designs of cables were installed with little or no water precautions. Within a few years, a large number of cables started to fail in service. Upon examination, tree-like structures were seen to have grown through the insulation. It was assumed that they continued to grow and failure occurred when the whole insulation was breached. This is the phenomenon of water treeing [1–3, 21].

Many studies have been carried out into the phenomena and its solution. Looking back, it is clear that a number of improvements in cable design, manufacture, and materials have reduced the incidence of cable failures by water treeing. These improvements have included

- Water barriers (metal or polymeric) to exclude the water
- Triple extrusion (all polymer layers extruded at the same time)
- Semiconductive polymer screens to replace carbon paint or paper tapes
- Cleaner insulations
- Smoother semicons
- Internationally recognized approval methods
- Special long life insulations based either on additives or polymer structure

The laboratory studies have concluded that the growth of water trees is affected by:

- Test voltage
- Test frequency

- Mean temperature
- Temperature gradient
- Type of material
- Presence of water (external and within the conductor)

There are essentially two types of water trees: (a) vented trees that grow across the insulation and are potentially the most dangerous and (b) bow-tie trees that grow across the insulation and tend to grow to a limiting size without breaching the insulation. These trees do *not* comprise tubules containing water as might be surmised from the earlier description of electrical trees. The "branches" of a water tree actually appear to comprise a high density of water-filled voids of typical diameter 1–10 μm. Such branches are therefore similar to a "string of pearls," but in practice, even branches of water trees are not usually discernible. They are simply diffuse regions of water-filled voids. If dried up, re-immersion in water reopens the voids. Boiling stabilizes the structure but probably also produces extra small voids. There is limited evidence that a percolation network does interconnect the voids, but the size scale of the interconnecting features is at around 10 nm. Electrolyte material accompanies the water into the voids and the ability of cationic dyes, such as rhodamine B, to stain the trees permanently indicates that some oxidation must have taken place. Chemical modification has also been shown using IR and FTIR spectroscopy and by fluorescence techniques.

Water trees grow much more slowly than electrical trees. Typically, they may not be observed at all for several years, even if the prevailing conditions for their growth are in place. They will then grow fast initially and then very slowly. Indeed, in the case of bow-tie water trees, there is much evidence that they stop growing completely after a given length (dependent on prevailing conditions) and that they might not precipitate breakdown. Vented water trees may cross the insulation completely without breakdown occurring, but they do greatly weaken the insulation. Generally, an electrical tree or a breakdown path may grow back through an electrical tree.

It is important to recognize that water trees occur in all extruded insulations (EPR, WTRXLPE, XLPE) and have been found in failure locations retrieved from service. It is often suggested that the water tree–retarding insulations (EPR and WTRXLPE) do not grow water trees. Unfortunately, this is not correct, though it is more difficult to detect water trees in these insulations; however, this is due to the lower initiation and growth rates (EPR and WTRXLPE) and the opaque nature of the insulation (EPR). Nevertheless, longer endurances and lower failure rates are seen for EPR and WTRXLPE for comparable designs and ages, with respect to cable XLPE analogues.

There are many proposed mechanisms of water treeing and these have been critically reviewed in Reference [12]. Essentially, it is likely that solvated ions are injected at partially oxidized sites. These catalyze further oxidation by maintaining the ion concentration. A sequence of metal-ion-catalyzed reactions is proposed in which bonds break and cause microvoids to develop. Alternating electromechanical stresses open up pathways for solvated ions; these initiate new microvoids. Many tree-retardant polymers contain "ion catchers" to prevent the metal ion catalysis, and these have been found to successfully delay the onset and growth rate of water trees.

The tree inception time, i.e., the time between the conditions being right for water tree growth and the first observation of water trees, is highly dependent upon the electrical stress. Typically, the inception time is inversely proportional to a high power (≈4–10) of electric field. For this reason, low-voltage cables, which tend to run at lower electric fields, may not have a water barrier to prevent water ingress and hence electrical treeing. In such cases, with fields typically <4 kV/mm (see Table 7.3), the probability of failure through electrical treeing is low and a water barrier would make little difference. HV and EHV polymer–insulated cables generally use water barriers, and these become mandatory above 66 kV. Furthermore, the conductor is often water blocked (a water-swellable compound or an extruded mastic) to prevent the transport of water along the conductor. The water may enter the conductor either after a cable breakdown or during installation or through an incorrectly installed accessory.

Dry Aging: Thermoelectric Aging

The requirement for extra high voltage (EHV) underground power cables is increasing [1, 2, 12, 14, 22, 23]. There is commercial pressure to push the mean electric field in the insulation of such cables toward 16 kV/mm, and the most common insulation used is cross-linked polyethylene (XLPE). Long-term experience of XLPE, however, is limited to moderately stressed cables with mean fields of 5–7 kV/mm. Furthermore, the introduction of cross-linking processes has permitted the continuous operating temperature of polymeric cables (XLPE and EPR) to be increased to 90°C, equaling that of oil-filled (LPOF and HPOF) paper and polypropylene paper laminate (PPLP) cables. The use of XLPE as the insulation for transmission cables has grown steadily since the early 1990s. Many extruded power cables have been operating for 20 years and are approaching the end of their 30-year design life. If robust methodologies could be found for improving or/and evaluating the reliability of AC power cables, it may be possible to continue to use them without compromising the reliability of the system. Such methodologies require considerable improvements in the understanding of any aging or degradation mechanisms of cable insulation. They would enable XLPE cables to be more competitive at EHV levels.

Future Directions

When looking at the history of underground power cable systems, it is possible to discern a number of rather constant trends:

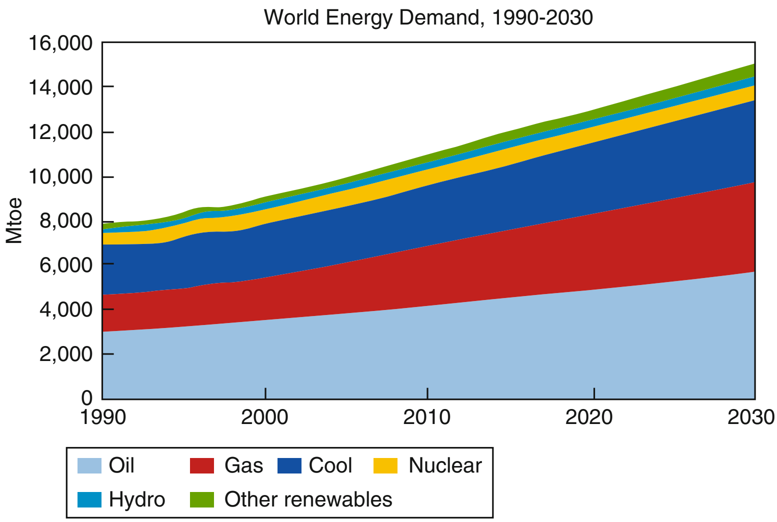

Fig. 7.8 Estimated world energy demand including split of primary energy sources [24]

- Longer length systems get installed as service experience increases.
- Utilities are looking for technologies with easier and less expensive installation and maintenance.
- Manufacturing and material technologies permit higher operating stresses leading to reduced wall thicknesses.
- Reduced wall thicknesses:
  - Lower the total installed system costs
  - Improve the thermal capacity
  - Place greater strains on the accessory and cable installation practices
- End users are looking for longer lives, though the end of life criteria remain undefined.
- Higher reliabilities for systems.
- Public pressure on the location of transmission lines underground.
- Increasing use of underground distribution cables in urban and suburban areas.

It seems clear that all of these trends will continue in the foreseeable future.

Considering the growth of energy requirement (Fig. 7.8), the increasing environmental awareness and the ever-growing level of information transfer, it can be seen that there will be a need to widen our future considerations to include:

- Much lower levels of electrical losses within the transmission and distribution systems – required for increased efficiency
- Higher attention to electric and magnetic field issues – required for increased acceptance of cable systems

- Even higher levels of urban undergrounding to improve the visual environment – required for increased acceptance of electric energy [25, 26]
- Integration of data and energy transmission – required for increased control and optimal use of corridors
- Improved levels of power delivery reliability as there is increasing reliance on more electrically powered systems – required for increased customer satisfaction

There can be no doubt that the use and importance of cables will increase.
The areas where most activity will be seen are:

- Understanding life expectancy of cable systems
- Improving cable performance with respect to aging
- Recyclable/recoverable cable designs
- Increased use of long length links
- Diagnostic trends for cable systems
- Impact of smart grid initiatives
- High temperature superconductivity (HTS)
- Gas-insulated lines (GIL)

Understanding Life Expectancy of Cable Systems

Utilities the world over continue to strive to increase the useful life of their underground or subsea cable system assets. However, this activity is taking place in an environment where there is an absence of any actuarial life expectancy or a good understanding of the factors that determine the end of useful life of a cable system. This does not mean that some of the causes of failure are not understood, in fact an extensive amount of work has been done on early failures in the 15–30 year range (e.g., water treeing, effects of contaminants). Thus, the life estimate for cable systems of 40 years is difficult to justify in any rigorous way.

A good example of the issues is the case of MV PILC cables installed in the USA [11]. These cables make up 15% of the total US installed capacity; however, in certain critical locales, this can rise to 80%. The median age of the oldest of these cables is 80 year with lower and upper quartiles at 70 and 90 years. Yet these cables are not failing at a rate that is discernibly higher than the average population of PILC cables: median age of 44 years. Thus, it is not possible to classify them as reaching the end of life because they are old or when they have not reached the right-hand portion of the "bathtub curve." It is equally unhelpful to assert that these cables have an infinite life as it is known that the paper and oil components will inexorably degrade.

These concerns become important when considering the economics/reliability and sustainability of any technology: The impact of a system that might last for 60 years is considerably less than today's arbitrary estimate of 30–40 years.

Improving Cable Performance with Respect to Aging

If one builds on the life expectancy concepts discussed previously, then it becomes possible to ascribe a value to technologies that might increase that longevity. Figure 7.9 shows the financial benefits of improved reliability within MV system. The experience over the recent past has shown that the most efficient way to measure and assure cable reliability is to require long-term wet aging tests (CENELEC – 2 years and ICEA – 1 year) with success levels that comfortably exceed the specified minimums.

The total cost perspective of two cable installations is shown in Fig. 7.9. The first shows the classic reference scenario, where the installed cost of cables is higher than the overhead analogue but the total lifetime cost is lower (92%). The second shows the scenario where a longer-lived cable has a longer life (30 years rather than 25 years in the reference) and lower operational costs, due to the better reliability throughout the longer life. Clearly the total cost is lower (82%) for the longer-lived cable. This approach is even more favorable than shown here for the higher-quality, longer-lived, cable; this is because the reference scenario would require that the cable and installation costs be incurred again in years 25–30.

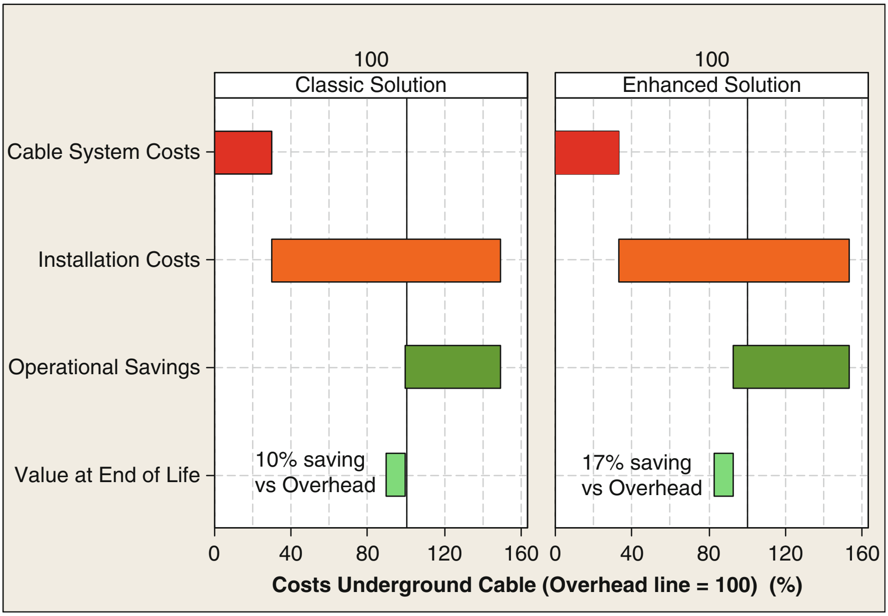

Fig. 7.9 Total cost perspective of two cable installations when compared to an Overhead Line. Initial costs are significantly offset by operational (maintenance, losses, and unreliability – all of these are assumed to be constant over a 30-year period) costs. Two cases are shown: 25 year life is the base case; the other is where a 10% higher cable cost brings higher quality and a 20% increase in life length (30 years)

Table 7.10 110kV Cable versus overhead cost (excluding permitting cost and time). Studies from The Technical University of Graz [26]

Type	Loading conditions	Installed costs (Euros/km)	Operating costs (Euros/km)	Total lifetime costs (Euros/km)	Cost ratio cables to overhead lines
Overhead lines	Low Load	149,000	15,000	164,000	**1.18**
Underground cable		181,000	12,000	193,000	
Overhead lines	High Load	149,000	165,000	314,000	**0.76**
Underground cable		181,000	58,000	239,000	

A similar story is seen at HV: In Austria, a very detailed study of total lifetime costs at 110 kV (Table 7.10) shows that cables have lower costs compared to overhead lines when the normal high loading of lines is considered. The ratios favor overhead lines at low loading but the gap is likely to narrow when the cost of obtaining wayleaves and negative customer/regulator pressure is included [26].

Recyclable/Recoverable Cable Designs

Today there is little activity associated with the recovery of abandoned cable systems as it is believed that there is little economic value associated with them. However, this may well change in the future as:

- There is likely to be public and environmental pressure to rehabilitate the land.
- The cables represent considerable natural resources.
- There will be a pressure to reuse the land previously used for cables and more importantly their associated substations/transformers/switches.

Evidence of these trends can be seen in the recovery of submarine fluid-filled cables (such as those that previously lay in Long Island Sound); here the regulation authorities required their removal as a prerequisite to the installation of new links. This reuses the structures can be seen with the replacement of gas compression cables in Germany and other places with extruded cables; but thie the reuse of the existing pipes/containment structures.

One of the limitations on recycling is the mixed nature of the nonmetallic components, i.e., the insulations and jackets [27]. This is because it is relatively simple to separate metals and metals from paper/plastic. However the plastic separation is not straightforward. Thus, to enable this separation in the future, the key element is the use of a whole polyolefin concept: XLPE and a HDPE jacket. With this approach the material mass is low and there is no expensive ($50/T at 2003 costs) separation step at the end of useful life. The metal within the cable may be reused, and the energy content of the polymer will be liberated and provide a value extremely close to the prevailing cost of oil, which is likely to be significant in 25–30 years' time [27].

Increased Use of Long Length Links

Submarine Cable Systems

Submarine power cables is the term given to cables that carry power underwater. They may be major transmission systems running under the sea, river crossings, or links to islands. Most submarine cable systems, of short to moderate length, are AC, whereas very long lengths employ DC (see later). The reason for the preference for AC is the simplicity of integration with existing infrastructures. The AC embodiments suffer from reactive losses, due to the natural capacitance and inductive properties of wire; hence, there are limitations on length. However, considerable accommodations can be made with solid state control devices and reactive compensation. DC transmission does not suffer reactive losses; the losses in the DC transmission line are the resistive losses. However, the losses in the AC/DC converters need to be included. Furthermore, the converter stations are a considerable capital and maintenance cost. However, from a pure power delivery standpoint, a DC cable system will carry between 1.3 and 1.6 times the power of an equivalently sized AC analogue.

Submarine cables are considerably longer than their terrestrial analogues: hundreds of kilometers versus tens of kilometers. They are laid in very long lengths from a variety of barges or ships. Thus, the manufacture and reliability requirements are much more challenging than for land cables. The importance of these considerations is obvious when the actions for repair after a failure in service are considered. The parties involved need to mobilize considerable marine resources, locate suitable repair materiel, obtain necessary environmental permits, physically attend to the site, retrieve the cable from the ocean floor, effect a repair, and confirm the integrity of the repair. If these elements are not challenging enough, the user and manufacturer need to determine some means to reestablish their confidence in the future problem-free operation of the link. Thus the design, specification, testing, manufacture and installation phases of a submarine project are many orders of magnitude more onerous than a similar terrestrial solution.

Nevertheless, in the future, it is clear that power grids will install larger amounts of submarine cable systems; the drivers will be:

- Increased network interconnection and stability
- Power trading
- Elimination of costly and inefficient local generation (islands)
- Integration of hydro and wind energy
- Reduced public reaction with respect to terrestrial power links

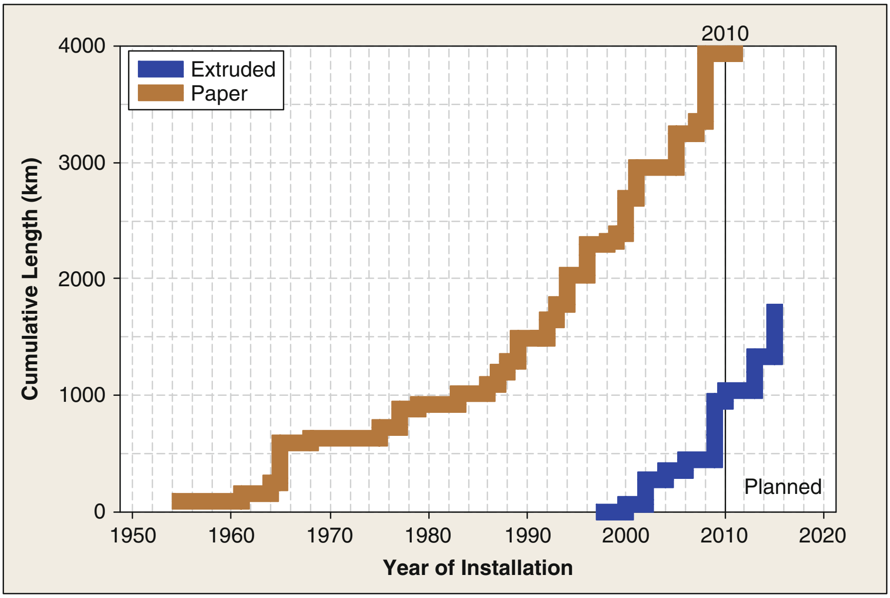

Fig. 7.10 Global installed DC cable capacity segregated by type of cable insulation

Efficient DC Power Transmission

Direct current (DC) power transmission has been shown to be highly efficient for highly controlled long-distance delivery (experience in Nordpool). Long-distance AC transmission is possible (Horns Rev and Isle of Man); however, it requires complex system control and reactive compensation of the cable capacitance. Thus, today the only technology that is capable of delivering long-distance power utilizing underground cables is HVDC. Inspection of the Gotland, Cross Sound, Murraylink, Troll and Estlink projects shows us that voltage source converter (VSC) technology and cables manufactured with cross-linked polyethylene designed for the rigors of DC are already proven and in commercial use. It is interesting to note how many appliances used today operate with DC power supplies (PC, TVs, etc.) – perhaps Thomas Edison had it right all along!!

In the early days of DC, the increased cost of the converters limited its use to EHV grid interconnections (UK/France, Baltic Cable, etc.). However, recent innovations (VSC) in converter technology, cross-linked polyethylene cables, and the flexibility of system design have seen a very rapid growth of DC at high voltage (50–150 kV).

There have been interesting laboratory studies and qualifications of extruded cables using filled insulations at EHV; however, all of the world's commercial installations and the experience shown in Fig. 7.10 has been achieved with specially designed unfilled cross-linked materials. It is clear that unfilled cross-linked technology will be used when extruded cables are integrated into EHV DC systems.

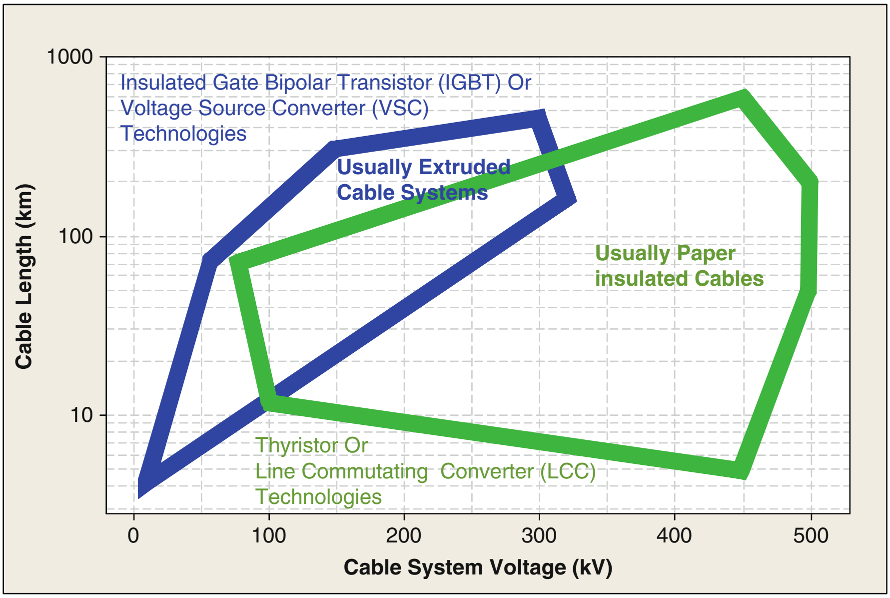

Fig. 7.11 Global installed DC cable capacity segregated by converter technology

The increased use of DC is being supported within the international committees. Specific recommendations have been prepared and published by CIGRE WG 21.01 within Technical Brochure 219. This document provides a very solid base for the extension to extruded HVDC cables. DC cable design presents the engineer with a coupled thermal and electrical problem with the stresses experienced by the cable depending upon the temperature and stress (polarity) inversions. There can be no doubt that HVDC cable design presents as many challenges as EHV ac systems. These include:

- Stress inversions
- Electrical stresses higher than those seen at EHV AC
- Ultralong lengths
- Testing and approvals
- Accessory technology
- System integration

However, as with EHV AC, careful attention to the insulation system makes it possible to succeed with some very impressive projects (Murraylink, Troll, and Cross Sound).

A complimentary aspect is the increasing usage of extruded cables using cross-linked DC polyethylene and voltage source converters (VSC) (Figs. 7.10 and 7.11). These developments have significantly increased the speed of implementation, lowered the total cost, and increased the types of projects for DC systems. It is interesting to reflect in Fig. 7.10 that paper systems required 30 years to achieve

1,000 km of cumulative installed capacity whereas extruded cables within 13 years. It is clear that the trend toward extruded cable systems with VSC technology will increase both in the submarine and terrestrial environments.

Diagnostic Trends for Cable Systems

The use of diagnostics on cable systems is growing and will clearly be an important part of network management for the future. New cables and accessories will probably have features integrated into them that will provide significant amounts of data. Older systems do not benefit from these developments, and thus, a diagnosis will need to be made without optimal sensors and a baseline condition. Nevertheless, considerable advances have been made. However, the challenge for cable and system engineers will come in transforming these data into useful information. Although the new installations will bring exciting opportunities, the major challenge will be associated with the "dumb" cable systems of today and yesterday.

The major areas of activity for diagnostics are:

- Real-time control of cable system rating – This is normally achieved through the use of fiber-optic temperature systems which are coupled to sophisticated thermal models of the cable system.
- Cable system commissioning/acceptance tests – Cable system components are separately tested in the factory; however, there is overwhelming consensus that most of the cable system issues are associated to incidents that occur during installation. Thus, there is a growing trend for cable system acceptance tests which permit these defects to be detected prior to acceptance for service, thereby enabling repair in a timely and cost-effective manner.
- Cable system diagnostic tests [11] – These are tests where the "health" of the cable system is determined, together with essentially a probabilistic assessment of future performance. These results enable a proactive level of asset optimization within the operator.

Real-time control of cable system and cable system commissioning tests are well established, and mature approaches and implementation is proceeding through international standardization bodies such as CIGRE and IEC. In many cases, the challenge is not technical but is the availability of the appropriate knowledge within the user community on the appropriate implementation.

Cable System Diagnostic Tests

Almost all electric power utilities distribute a portion of the electric energy they sell via underground cable systems. Collectively, these systems form a vast and valuable infrastructure. Estimates indicate that underground cables represent 15–20% of installed distribution system capacity. Utilities have a long history of using underground system with some of these cable systems installed as early as the 1920s. Very large quantities of cable circuits were installed in the 1970s and 1980s due to the introduction of economical, polymer-based insulation compounds and the decreasing acceptance of overhead distribution lines. Today, the size of that infrastructure continues to increase rapidly as the majority of newly installed electric distribution lines are placed underground.

Cable systems are designed to have a long life with high reliability. However, the useful life is not infinite. These systems age and ultimately reach the end of their reliable service lives. Estimates set the design life of underground cable systems installed in the range of 30–40 years. Today, a large portion of this cable system infrastructure is reaching the end of its design life, and there is evidence that some of this infrastructure is reaching the end of its reliable service life. This is a result of natural aging phenomena as well as the fact that the immature technology used in some early cable systems is decidedly inferior compared to technologies used today. Increasing failure rates on these older systems are now adversely impacting system reliability, and it is readily apparent that action is necessary to manage the consequences of this trend.

Complete replacement of old or failing cable systems is not an option. Many billions of dollars and new manufacturing facilities would be required. Electric utilities and cable/cable accessory manufacturers are simply not in a position to make this kind of investment.

However, complete replacement of these systems may not be required because cable systems do not age uniformly. Cable researchers have determined that many cable system failures are caused by isolated cable lengths or isolated defects within a specific circuit segment. Thus, the key to managing this process is to find these "bad actors" and to proactively replace them before their repeated failures degrade overall system reliability. Various cable system diagnostic testing technologies were developed to detect cable system deterioration. The results of diagnostic tests are used to identify potential failures within cable systems and then again, after repair, to verify that the repair work performed did indeed resolve the problem(s) detected.

Appropriate maintenance and repair practices enable system aging to be controlled and help manage end-of-life replacements. Diagnostics to determine the health of the cable system are critical to this management program.

A number of cable diagnostic techniques are now offered by a variety of service providers and equipment vendors. However, no one service has definitively demonstrated an ability to reliably assess the condition of the wide variety of cable systems currently in service. Implementing cable system diagnostics in an effective way involves the management of a number of different issues. This includes the type of system (network, loop, or radial), the load characteristics (residential, commercial, high density, government, health care, etc.), the system dielectric (XLPE, EPR, paper, mixed), and system construction (direct buried or conduit). The basic cable diagnostic testing technologies used to assess cable circuit conditions are listed below.

- Time domain reflectometry (TDR)
- Partial discharge (PD) at operating, elevated 60 Hz, elevated Very Low Frequencies (VLF) or damped AC (DAC) Voltages [11, 28]
- Tan δ/dielectric spectroscopy at 60 Hz, VLF or variable frequencies [28–30]
- Recovery voltage
- DC leakage current
- Polarization and depolarization current
- Simple withstand tests at elevated VLF, 60 Hz AC, or DC Voltages [11, 31]
- Acoustic PD techniques
- Monitored withstand tests at elevated VLF, 60 Hz AC, or DC voltages with simultaneous monitoring of PD, tan δ, or Leakage Current [11, 31]
- Combined diagnostic tests at 60 Hz AC, very low frequencies (VLF), or damped AC (DAC) voltages using PD and tan δ

There is no doubt that cable system diagnostic testing can be used to improve system reliability. However, to be effective, the technology should be appropriate to the circuit to be tested. Setting accurate and reasonable expectations is also a critical part of the process.

In general, the work performed in the CDFI [11] led to the following observations:

- Diagnostic tests can work. They often show many useful things about the condition of a cable circuit, but not everything desired.
- Diagnostics do not work in all situations. There are times when the circuit is too complex for the diagnostic technology to accurately detect the true condition of the circuit.
- Diagnostics are generally unable to determine definitively the longevity of the circuit under test. Cable diagnostics are much like medical diagnostics. They can often tell when something is wrong (degraded), but it is virtually impossible to predict the degree to which a detected defect will impact the life of the system tested.
- Field data analysis indicates that most diagnostic technologies examined do a good job of accurately establishing that a cable circuit is “good.” They are not as good at establishing which circuits are “bad.” In most cases, there are far more good cable segments than bad segments. However, it is virtually impossible to know which “bad” circuits will actually fail. Therefore, utilities must act on all replacement and repair recommendations to achieve improved reliability.
- The performance of a diagnostic program depends on:
  - Where diagnosis is used?
  - When diagnosis is used?
  - Which diagnosis to use?
  - What is done afterward?
- A quantitative analysis of diagnostic field test data is very complex. The data comes in many different formats and the level of detail is extremely variable.

However, an in-depth analysis of the data clearly highlights the benefits of diagnostic testing.
- Diagnostic data require skilled interpretation to establish how to act. In almost all cases, the tests generate data requiring detailed study before a decision can be made on whether to repair or replace the tested cable circuit.
- No one diagnostic is likely to provide sufficient information to accurately establish the condition of a cable circuit.

Impact of Smart Grid Initiatives

Much has been written about Smart Grid Initiatives. Smart grid is defined rather differently in Europe and USA; however, one commonality is that the goal is to insert intelligent and interactive devices in the existing grid infrastructure to fulfill a number of goals, such as:

- Better facilitate the connection and operation of generators of all sizes and technologies
- Allow consumers to play a part in optimizing the operation of the system
- Significantly reduce the environmental impact of the whole electricity supply system
- Maintain or even improve the existing high levels of system reliability, quality, and security of supply
- Dynamic optimization of grid operations and resources, with full cyber-security
- Deployment and integration of distributed resources and generation, including renewable resources
- Development and incorporation of demand response, demand-side resources, and energy-efficiency resources
- Deployment of "smart" technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation
- Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning

Thus, it is clear that the existing grid will be operated in a different manner to the one that it is accustomed and that the demands placed upon it will be increased. A natural consequence will be that a number of hitherto unseen failure or degradation modes will become prevalent. It is already possible to postulate what a number of them might be:

- Overheating of nonoptimally designed/installed components, which have not presented themselves due to the lower level of grid loading [32]

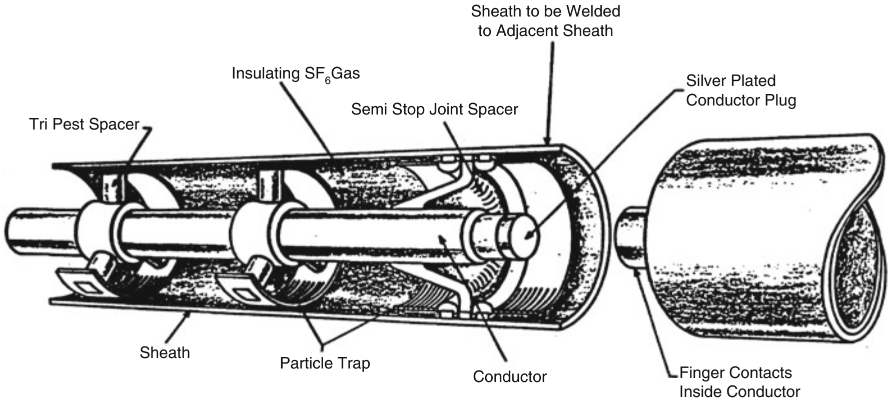

Fig. 7.12 Typical design of a gas-insulated line (GIL)

- Accelerated degradation due to transients/harmonics superposed on the grid by the smart devices themselves, the most obvious are third, and higher, harmonics
- A heightened sensitivity of consumers to power quality issues
- More aggressive load profiles due to changing demand and supply side protocols, as a consequence of reducing the traditional "low load recovery periods"

High-Temperature Superconductivity (HTS)

Equally there are technologies of today that will find some niche uses, but are unlikely to come into immediate and widespread use. The first is high-temperature superconductivity (HTS) that may well find application where people wish to transmit large amounts of power over relatively short distances. However, the issues associated with long-distance cryogenics, termination temperature differences, and complicated start-up procedures need to be addressed before this technology becomes attractive to utilities.

Gas-Insulated Lines (GIL)

Gas-insulated Lines offer the hope of large current ratings, low capacitances, and reduced dielectric losses for longer transmission distances. Yet, in most practical cases, the short lengths, and the associated difficulties of fabrication, plus the large environmental issues around large amounts of SF_6 gas, even in mixtures, will limit its use. By comparison, it would seem that GIL has much wider application than superconducting cables. A typical gas-insulated line design is shown in Fig. 7.12.

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