Citation: Fothergill, J. (2014). The coming of Age of HVDC extruded power cables. In: Electrical Insulation Conference (EIC), 2014. (pp. 124-137). IEEE. ISBN 9781479927876 doi: 10.1109/EIC.2014.6869361

The Coming of Age of HVDC Extruded Power Cables

John C Fothergill
Pro Vice-Chancellor (Research and Enterprise)
City University London
London, UK
john.fothergill.1@city.ac.uk

***Abstract*—High voltage DC (HVDC) transmission systems have the potential to transform major electrical grids; they can deliver very high powers over long distances with high efficiency and reliability. Cables are required for subsea and underground systems. Extruded cables – i.e. those with polymeric insulation – have been successfully used in AC applications for 40 years or more and have developed to overcome some of the early problems encountered with water and electrical trees. Such extruded cables have advantages in terms of manufacturing, maintenance and reliability over lapped paper and oil systems. Lessons have been learnt from early experiences with AC cables that may be useful in the development of DC cables. DC cables, however, also provide a new set of insulation challenges, primarily associated with the control of conductivity and space charge, which may lead to very high internal electric fields building up in the insulation. Techniques for measuring space charge and conduction are described and discussed in terms of how they might be used to quantify the state of a HVDC cable. Nanodielectrics are likely to play a part in the development of new materials for their insulation. With an understanding of the key processes to control, techniques to control them and new materials, manufacturers now seem keen to embrace extruded power cable technology for HVDC applications. The paper gives a personal perspective on the development of these cables and links it with the author's research over the last 30 years.**

Keywords—HVDC; high voltage, power transmission, power cable, XLPE, electrical tree, water tree, space charge, conductivity, nanodieletric

I. INTRODUCTION (HEADING 1)

When Greg Stone gave his Dakin Award lecture at the IEEE International Symposium on Electrical Insulation held in San Juan, PR, in June 2012, he talked about his personal perspective on on-line partial discharge monitoring to assess the condition of rotating machine stator winding insulation. For some time, I seem to have followed in Greg's footsteps, for example, when I re-wrote his 1987 IEEE Standard in 2004 as IEEE Std 930-2004: IEEE Guide for the Statistical Analysis of Electrical Insulation Breakdown Data [1] with Gian Carlo Montanari - and so it seemed a reasonable idea to talk about "my personal perspective" on HVDC Extruded Power Cables.

I was recently delighted to be asked to write a preface for an excellent and timely book by Giovanni Mazzanti and Massimo Marzinotto on Extruded Cables for High-Voltage Direct-Current Transmission [1]. In this, I pointed out that high-voltage direct-current (HVDC) transmission is not new; indeed Edison constructed a 45 km link as long ago as 1882. It may therefore come as a surprise that, in the title, I suggest that HVDC Extruded Power Cables are only now coming of age. I hope to show that we now know the questions to ask and even some of the answers when evaluating such cables and perhaps the time for HVDC has come round again.

The time certainly seems to be right for exploiting HVDC transmission. Electricity grids used to be national but they now connect states, provinces and countries across continents. Whilst continents may be 4000 km "wide", AC cables cannot reach more than about 100 km (much less for very high voltages) and AC overhead lines become inefficient after a few 100 km. Pan-continental HVDC transmission would aid "power lopping" where consumers on the west coast may have high power requirements whilst cooking their dinner but those on the east coast consume little power as they are going to bed. Environmentally sustainable power sources, such as wind, hydro and massive PV arrays, tend to be some distance away from centres of population. For example the Three Gorges Dam in China, the largest power station, which produces up to 18.2 GW, feeds much of its power to cities such as Shanghai and Guangdong around 1000 km away; the latter uses a 3 GW HVDC link provided by ABB [2].

Our networks are getting congested: on occasions 90% of the power transmitted in Belgium is not being used by Belgians, it is being transmitted though the country from Germany to France. Many of our current electrical transmission networks are analogous to road networks without motorways (or interstate highways as I believe the Americans call them). HVDC systems offer the possibility of high power transmission with low loss over very long distances – they could be the electrical superhighways that we need. Such links allow connections between asynchronous AC systems and may help to prevent cascading failures of the type that left 50 million people without electricity in the north-eastern and Midwestern US states and Ontario in August 2003. Synchronicity may well become more difficult to achieve with more rapidly changing power transmission levels associated with sustainable sources and the implementation of smart grids.

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[1] This standard has been co-branded and has been issued as an IEC Standard 62539/IEEE 930. Nigel Hampton, Robert Ross, and indeed Greg Stone also made contributions.

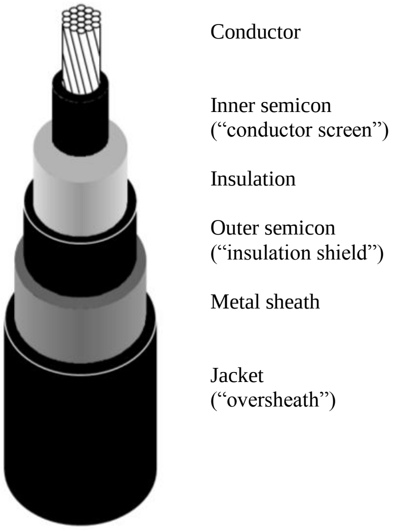
Whilst the use of power cables undersea is well established, the use of buried power cables, rather than overhead lines, would allow much narrower rights of way, elicit more sympathy from countryside campaign groups [3], and protect cables from storms and flooding. The ratio of the cost of burying cables to using overhead lines has reduced considerably from the traditional rule-of-thumb figures of 10 or 20. A UK government planning body, the Infrastructure Planning Commission, commissioned a report [4], overseen by the IET and prepared by engineering consultants Parsons Brinckerhoff into the comparative costs of routing transmission lines which found that underground cabling was approximately five times more expensive than traditional overhead pylons. (Over 40 years, overhead lines were estimated to cost between £2.2M/km and £4.2M/km compared with £10.2M/km and £24M/km for buried cables depending on the voltage, length and technology used.)

I am not sure whether it was by design or accident or "in a cloud of unknowing"[2] but much of my research has found application in the area of extruded power cables, and seems to be useful for HVDC technologies. So in this rather personal account I focus on some contributions to this area that both demonstrate some of the challenges of developing DC extruded power cables as well as some of the opportunities.

A. Power Cable Development

Power cables have a co-axial structure, the principal components of which are shown in Fig. 1. There is a current-carrying conductor operating at the line or phase voltage, usually made of copper or aluminium. Surrounding this is insulation, which may be an extruded plastic such as super-clean crosslinked polyethylene. To prevent splinter-like protrusions forming from the central conductor and sticking into the polymer insulation, which would cause field enhancing points, the conductor is surrounding by conductive plastic. The interface between this so-called "semicon" and the insulation is designed to be as smooth as possible. As well as preventing metallic protrusions, the semicon also has similar thermal characteristics to the polymer insulation and prevents significant differential contractions between the insulating and conducting parts of the cable as the conductor heats up and cools down. Similarly, on the outside of the insulation, there is another semicon, which is connected to an earthed or return conductor. To prevent the ingress of water, there may be a metallic shield surrounding the outer semicon.

In Harry Orton's recent article (dedicated to the memory of Professor John Tanaka) on the History of Underground Power Cables [5], he charts the development of power cables. Whilst it can be seen that polyethylene (PE) insulated cables were being developed as far back as 1942, the first use of crosslinked polyethylene (XLPE) was not until 1968. The "crosslinking" process, which is analogous to the vulcanisation of rubber, joins together the long polyethylene molecules ($- CH_2 - CH_2 - CH_2 -$) with chemical links, effectively making the insulation into one gigantic molecule. XLPE does not flow above the melting point of the polyethylene (~107°C); it becomes like a gel. The cable conductor can therefore be allowed to run at higher temperatures, typically up to 90°C rather than the 70°C allowable for an uncrosslinked PE. Permissible short circuit currents may be 20 times the standard current rating. Some key dates in the development of XLPE cables are [5]:



1968	First use of XLPE cables for MV (mostly unjacketed, tape shields)
1972	Introduction of extruded semiconductive screens
1973	Superclean materials used (Sweden)
1978	Widespread use of polymeric jackets in North America
1982	Water-tree retarding insulating materials introduced for MV in United States and Germany
1989	Supersmooth conductor shields introduced for MV cable in North America
1990	Widespread use of water-tree retarding insulating materials

It can be seen from this that the introduction of extruded techniques for power cables did not go that smoothly. The cables that were introduced in the late 1960's had a short life; the requirements for physical and chemical purity of the XLPE, i.e. the exclusion of contaminants and voids, and the prevention of protrusions were not initially appreciated by manufacturers. This is well described by John Densley in the first Eric O. Forster Memorial Lecture [6], which he gave at a conference I was proud to have chaired in 1995. (Eric had actually convinced me, at the 1992 conference in this series, held in Sestri Levante in Italy, to chair the 1995 conference in Leicester, UK. Sadly, he passed away in December 1993. His family kindly allowed us to name the opening plenary lecture of the conference in his name.) There was also little appreciation that water – or at least humidity - could present a danger to the XLPE insulation, presumably because it was felt

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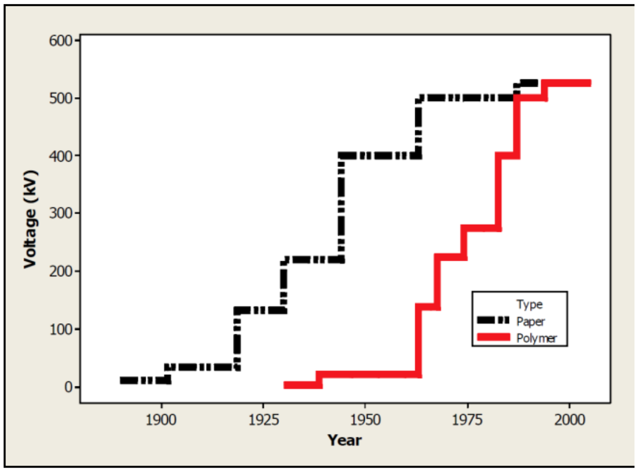
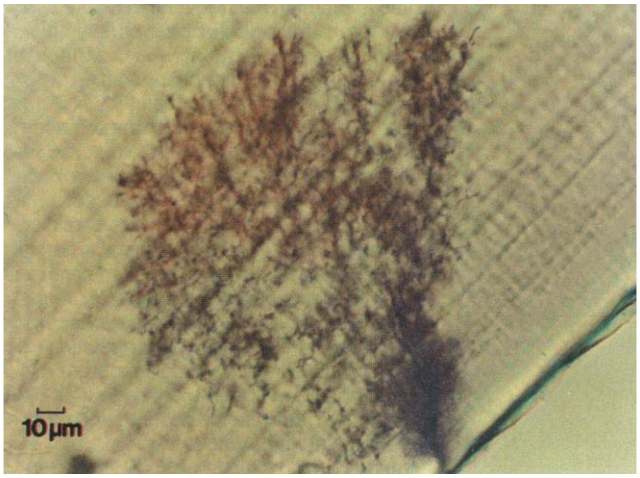
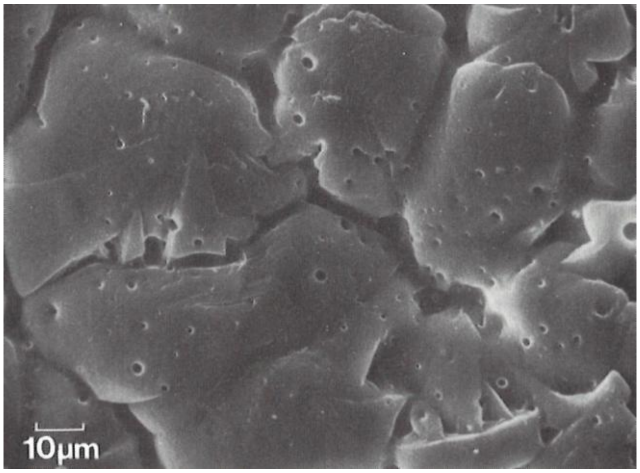
[2] "Accident is design, And design is accident, In a cloud of unknowing." T. S. Eliot, The Family Reunion (1939)







that the hydrophobic nature of the material would not allow a significant amount of water uptake. Typically the early cables only lasted 10 to 15 years, and, for every dollar the utilities spent on installing the cables, they spent 10 dollars replacing it [7]. Since then, however, considerable progress has been made and XLPE-insulated cables have reached high voltage levels (Figure 2) with low failure rates due to ageing of approximately ~0.1 failure per year per 100 km. (There are many more failures due to 3rd party damage [8].)

It was about the time that these problems started to emerge that I finished my PhD (on the "Electronic Properties on Biopolymers") under the supervision of Ron Pethig in the research group of John Lewis at what is now Bangor University in North Wales. My first job was at the Standard Telecommunication Laboratories (STL Ltd) in Harlow, Essex, where I worked on power cables for STK in Oslo, Norway and IKO, a large cable company in the tiny town of Grimsås in the south of Sweden. At the time, about half the population of Norway lived in Oslo in the south of the country whilst most of the electricity was generated by hydro power in the north; it was therefore necessary to transmit this over a distance of some 2000 km – there was therefore a lot of cable expertise in Scandinavia.

B. *Water Trees*

Some of the first work that I published from STL was on "water trees" (e.g. [9,10]). Water trees are a form of degradation that occurs in XLPE cable insulation under humid conditions under AC voltage. They can be visualised by staining, an example is shown in Fig. 3. Although these are termed "trees" because of their shape, the "branches" of the trees are not formed of continuous tubules or cracks; the path of the water tree is marked by the presence of a high concentration (~10^{15} m^{-3}) of spherical microvoids whose radius is <1 μm. These microvoids can be clearly seen under a scanning electron microscope, Fig. 4. The mechanism of the formation of water trees, and the dependence of their growth on conditions such as voltage, frequency, temperature, humidity, salt concentration, was not well understood. It is likely that ions, dissolved in the water, enter the polyethylene under the influence of the electrical field (which itself causes electromechanical strains) at sites that are partially oxidised. These ions aggregate, through a diffusion limited aggregation process, and catalyse further oxidation of the host polymer. Microvoids are produced by the polymer radicals with metal ions stabilising the void surfaces. Further transport of ions deeper into the polymer is facilitated through free volume "opened up" by more electromechanical forces and the process repeats forming another microvoid. It is noticeable that it is almost impossible to find any channels between the microvoids themselves, the free volume must therefore collapse when the electric field is removed. If the water trees are dried out, they quickly reform under the appropriate conditions for growth, showing that the damage to the polymer is permanent. The rather poetically-named "bow-tie" trees grow out from water-filled voids in the bulk of the insulation whilst those growing from the semicon are somewhat incorrectly named as vented trees. There is an excellent review of experimental observations of water treeing by Shaw and Shaw [12].

There are two common ways of preventing water trees in cables. The first rather obvious and pragmatic solution is to keep the water out. Many higher voltage subsea cables use a metal (typically lead) sheath moulded around the outer semicon (see Fig. 1). The conductors are also filled with water-blocking compounds that prevent water running along the conductor in the case of water ingress, possibly due to a cable breakage. During the 1980s water-tree retardant XLPE compounds were also produced. Whilst these proprietary compounds contain products only known to the manufacturers, it seems likely that they "catch" or are devoid of the ions that stabilise the microvoid formation.

The cyclic electromechanical forces that aid water penetration in water treeing will not exist under HVDC conditions and so one might expect that such systems are immune from this form of degradation. Of course, HVDC cables do not carry a perfectly smooth DC voltage, indeed there will be significant high-frequency AC components caused by the AC to DC converter power electronics. This combination does result in water tree formation with the combined DC and high frequency AC stress generating very long vented (i.e. dangerous) water trees. The initiation and growth rates are strongly determined by the AC component, whilst a high DC stress may impede the the water tree growth. [13]

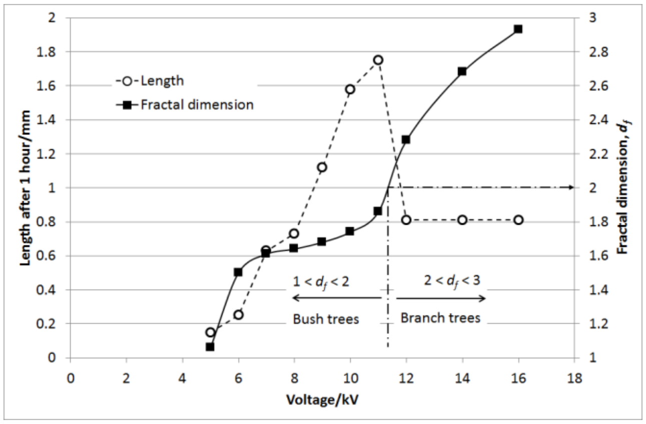
I collaborated with Len Dissado, who was a consultant at STL, on the early work on water treeing. We subsequently co-authored a book on "Electrical Degradation and Breakdown in Polymers" [14] and have worked together ever since. His theoretical analytical skills and better understanding of chemistry complemented my more practical skills coming from an electrical materials engineering background.

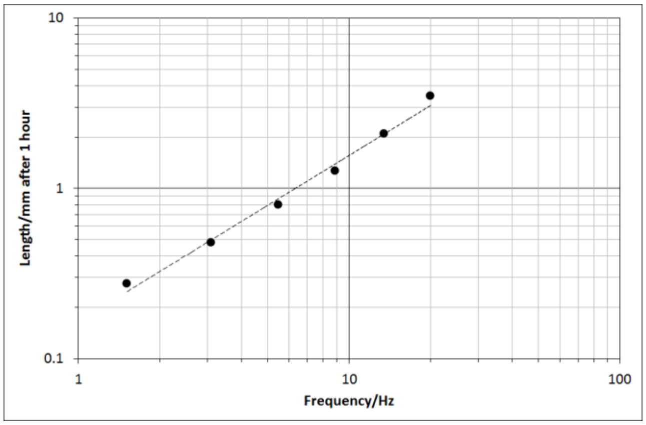
C. Partial discharges and electrical trees

Whilst at STL, I led the development of cable jointing using a moulding technique in which a small extruder was used in an attempt to maintain hydrostatic pressure on the extrudate whilst the mould was heated and cooled. I have to admit that this was never entirely satisfactory and I have no idea whether the problems associated with this have been resolved to the point where it is used. However, the testing of the joints involved the detection of partial discharges and so many hours were spent peering at Lissajous figures on an old ERA partial discharge detector and being disappointed if more than 10 pC were detected at 1.25 U_0. It seems likely that in the absence of cavities larger than some 10 μm, partial discharge can be discarded as a route towards failure. This is assumed because the mean free path for an electron in air at 1 bar is 70 nm, therefore within 1 micron, 14 subsequent ionizing collisions can occur which will give 2×10^4 electrons, far from the $\sim 10^8$ required. This was discussed in detail at a meeting, in the style of a Gordon Conference, supported by the Institute of Physics Dielectrics Group and the IEEE DEIS UK Chapter, which was held in Autrans, in the Vercors range of the Alps above Grenoble, France, in July 2011. One of the topics was 'Void growth through to sustainable partial discharge activity'. The word 'sustainable' suggests that such activity would lead to electrical treeing. It was also unclear whether 'void growth' (possibly through the coalescence of existing voids) could really occur. All of these also seem less likely under DC than AC conditions and so I was left with the impression that if the voids do not exist in the first place, it was unlikely that electrical trees would grow from spontaneously formed voids.

An example of an electrical tree is shown in Fig. 5. Since such trees are difficult to see in XLPE (it is not very transparent), the example shown here is one produced in epoxy resin by another long-standing co-worker and friend Dr Steve Dodd, who published a series of systematic experimental studies in this area in the early 1990s [15-18] with John Champion. Unlike water trees, these trees do consist of tubules which may support partial discharges depending upon the conductivity of the surrounding polymer and hence the field along the branch of the tree. Since the conductivity of the XLPE is very low, partial discharges would be expected in these long tubules. The electrons bombarding the positive end of the tubule give rise to charge injection into the polymer and field enhancement, at least on alternate half cycles. Furthermore, the high energy of the electrons is sufficient to break the chemical bonds holding the material together. Consequently, after sufficient discharging, a new tree branch is formed. A detailed theory of electrical tree formation was published with Len Dissado [19]. This work has also continued more recently [20-23].

The analysis of tree lengths as a function of voltage is fascinating. Trees were described by exotic names including bush, branch and even monkey-puzzle. The bush trees were densely packed with short branches such that the individual branches could not be seen easily whereas the branch trees were longer and sparser (Fig. 5 is a branch tree). Noto and Yoshimura [24] and John Densley [25] showed that branched trees grow at lower voltages and bush trees grow at higher voltages. The bush trees that are produced just above the crossover voltage are shorter than the branch trees that are produced just below the crossover voltage after the same period of growth. Note that as the voltage is increased through the crossover voltage the resulting tree is *shorter* rather than longer. Trees can be described mathematically by fractals [19] – such that bush trees have a 'fractal dimension', d_f, between 2 and 3 and branch trees (which are less space filling) have a d_f between 1 and 2. This is shown in Fig. 6. The fractal dimension (right hand axis) rises monotonically with voltage;





when this exceeds $d_f = 2$, (at just above 11.5 kV) the tree changes shape from branch to bush and the tree length reduces as the voltage is increased through this transition.

Using this technique it is possible to show that the length of the tree, *l*, is related to the total volume, *v*, of the tubules which comprise the branches of the tree by:

$$l = v^{\left(\frac{1}{d_f}\right)} \qquad (1)$$

It is reasonable to assume that the total volume is related monotonically to the number of partial discharges and that these are proportional to frequency. This is borne out by experimental results shown in Fig. 7.

Since electrical trees grow from regions of high stress – which are usually caused in extruded cable insulation by protrusions or voids – it is extremely important to avoid these during manufacture. They can also grow from water trees that have extended a long way (or even right through) the insulation.

Given that the rate of electrical tree growth is approximately proportional to frequency, one would expect that under DC conditions, it would be difficult for electrical trees to grow. The partial discharges required would be unipolar and so charge would need to be conducted through the XLPE both as a source and a sink of charge for the discharge. DC trees have been observed, especially where there are significant voltage transients or impulses [26]. It seems likely that significant partial discharges under HVDC are only to be found during switching (i.e. during voltage change) and even then is much more likely to occur in poorly made materials (See [27], which also makes suggestions for developing p.d. tests for HVDC cables over and above the CIGRÉ tests.)

So the two key problems for AC cables that had to be solved, i.e. water treeing and electrical treeing, appear not to be such a problem for DC cables, what could possibly go wrong?

II. AC VERSUS DC

A. *Example*

A power cable is a coaxial structure, which means that it is capacitive. Under AC conditions, the cable will therefore draw a displacement current to charge and discharge the cable capacitance. For example, consider a cable designed for a 500 kV 1GW 50Hz three-phase system, the phase to ground voltage for each of the three cables will be 290 kV (= 500/√3). The aluminium conductor diameter may be around 50 mm in diameter (carrying just over 1000 A) and the thickness of the XLPE approximately 30 mm. I.e. the inner radius of the insulation is approximately 25 mm and the outer radius is 55 mm. Expressed as per metre of cable, the capacitance is of the order 160 pF/m and, at 20°C, the resistance of the insulation is ~10^{16} Ω/m. If we consider a 10 km length of such a cable then the displacement current due solely to the cable capacitance is of the order of 145 A – i.e. around 15% of the total current carrying capacity of the cable. If the cable were operating under steady-state DC conditions, the current due to the finite conductivity of the insulation would be very small (~0.3 μA).

This difference in current through the insulation under AC and DC conditions is both the raison d'être for HVDC cables – the losses are much less over long distances – but it also gives rise to a fundamental problem.

B. *Field Control*

In an AC cable, the electric field at any given radius in the insulation as a function of the applied voltage is defined by the current density. Since the conduction current through the insulation is insignificant, we only need to consider the displacement current, which itself is defined by the permittivity of the insulation. The permittivity is not significantly dependent on the field or the temperature and can be considered as a constant (~2.3 for XLPE depending on the additives introduced by the manufacturer, etc.). The important point here is that the field is well defined for an AC cable. Fig. 8 shows the electric field for the example cable above; it is inversely proportional to the radial distance from the centre of the cable[3]. The ratio of the highest field (i.e. at the inner radius

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[3] We assume the current flows in a radial direction only. If we slice an incremental length out of the cable, we can then divide the insulation into a set of concentric rings. Each ring has the same total current flowing through it but the circumference of each ring is proportional to its radius. The current

of the insulation) to the lowest field (at the outer radius) is simply equal to the ratio of the outer to inner radii. In this example:

$$55\ \text{mm}/25\ \text{mm} = 0.22 = \ 14.71\ \text{kV/mm}/6.69\ \text{kV/mm}$$

Under DC conditions however, the situation may be quite different for two reasons:

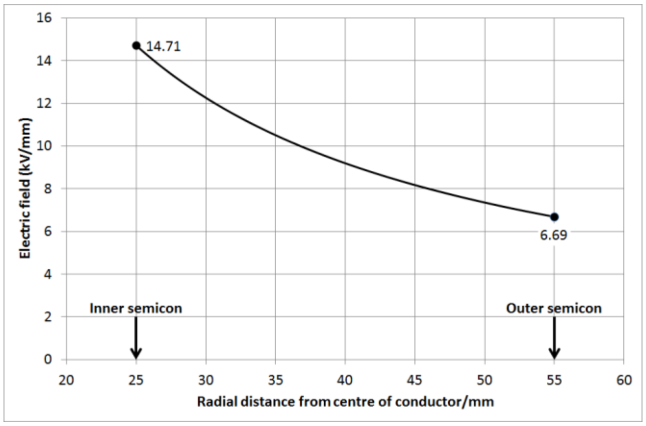
1) Dependence of conductivity on temperature and field

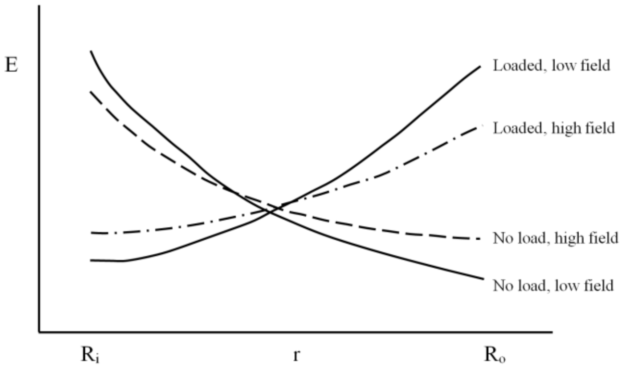
The DC field is controlled by the conductivity of the insulation, not its permittivity. Unlike the permittivity, the conductivity is highly dependent upon temperature and to some extent on electric field as well. The high currents flowing through the conductor cause joule (I^2R) heating, whilst the outside of the cable is cooled by the environment (surrounding earth, air, water, etc.). The XLPE insulation has a low thermal conductivity and so there is temperature drop with temperatures typically 30°C (or more) higher at the inner semicon that the outer semicon. The electrical resistvity of the XLPE adjacent to the inner semicon may be much less than next to the outer semicon and so the electric field may be much higher near the outer part of the insulation than the inner – a so-called 'field inversion'. Jeroense and Morshuis considered this in some detail for HVDC paper-insulated cables [28]. Fig. 9 is drawn from their paper and the field inversion effect is clearly seen. Note that when the electrical conductivity increases at high electric fields, the field enhancement is reduced somewhat. The effect in XLPE cables has been considered in some detail by one of my PhD students, Tong Liu [29] and an example is shown in Fig. 10. The onset of thermal breakdown can be seen at 340 kV (the 'maximum thermal voltage' or MTV).

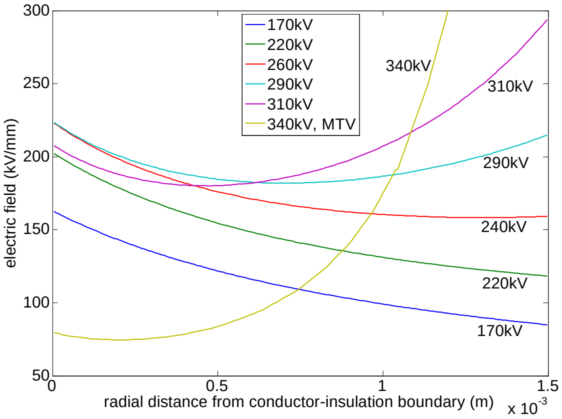
2) Space Charge Accumulation

In polymeric insulation, electrical charges (electrons, holes, ions) may be electrostatically attracted to points within the insulation to form chemical bonds or other points where there are counter charges due to physical defects or inhomogeneities. Detailed modelling of such traps has been the subject of investigations by Quirke *et al* [30]. Such charges are said to be trapped. Traps may be thought of as regions of low potential energy (rather like the bottom of a hole in the road has a lower gravitational potential energy than surface of the road) into which charges 'fall'. Charges can escape from traps by spontaneously gaining sufficient energy from thermal vibrations, etc. or the local physical conditions may change leading to the effective disappearance of the trap. High electric fields may also aid detrapping of charge. Charges may be trapped in shallow traps for as little as picoseconds, whilst they may remain in deep traps for many centuries; electrets rely on such deep traps to retain their piezoelectric effects. The residence time of charges in traps in polyethylene has also been calculated by Meunier and Quirke [31].

Space charge accumulates when there is an imbalance in the rate at which charge enters and leaves a region. For example, charge may be injected into the XLPE insulation from the semicon faster than it can be conducted away. In this case, negative space charge would accumulate near the negative semicon and positive space charge near the positive semicon – this is known as 'homocharge'. Alternatively, charge may be conducted away faster than it can be injected, in which the 'heterocharge' would be observed.







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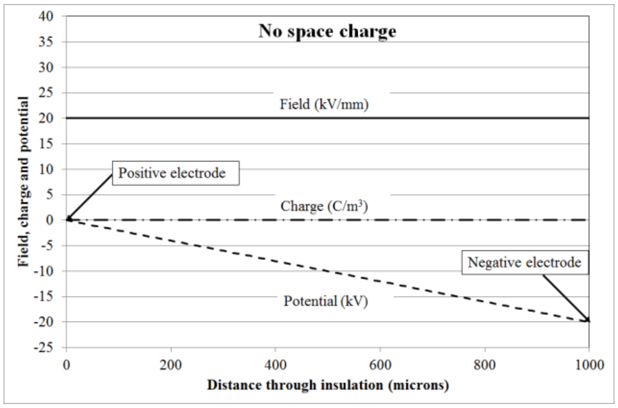
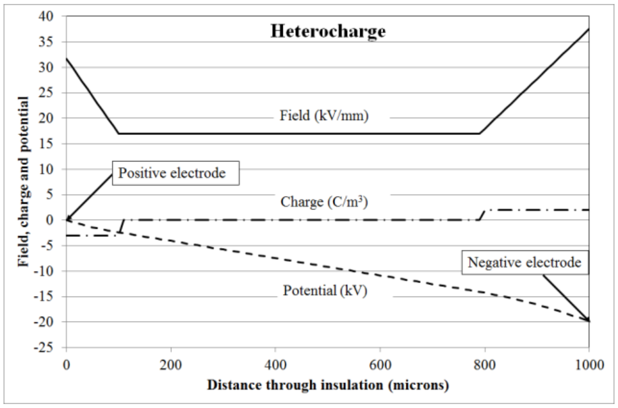
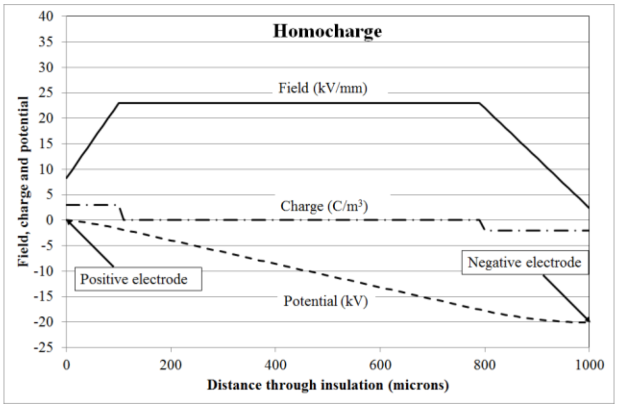
density, and hence the electric field, is therefore inversely proportional to the radius.







The average field in a dielectric is defined by the voltage across it and its thickness. However, when space charge is present, the field is distorted in that region. In the case of homocharge, the field near the semicon is reduced and the field in the bulk is increased to compensate. In some cases one could argue that this is a good situation as the interface with the semicon is often electrically weaker than the bulk. For heterocharge, the situation is reversed and the field is higher at the electrodes and lower in the bulk. The situation is shown in Fig. 11 for a slab of dielectric material, 1 mm thick with an applied voltage of 20 kV (the average field in each case is therefore 20 kV/mm). The relevant governing equation in one dimension is Poisson's equation:

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{\rho}{\varepsilon} \qquad (2)$$

where V is the voltage at position x, E is the electric field, ρ is the space charge density and ε ($=\varepsilon_r\varepsilon_0$) is the permittivity. For no space charge, i.e. $\rho = 0$, this becomes Laplace's equation and the electric field is sometimes referred to as the 'Laplacian field'.

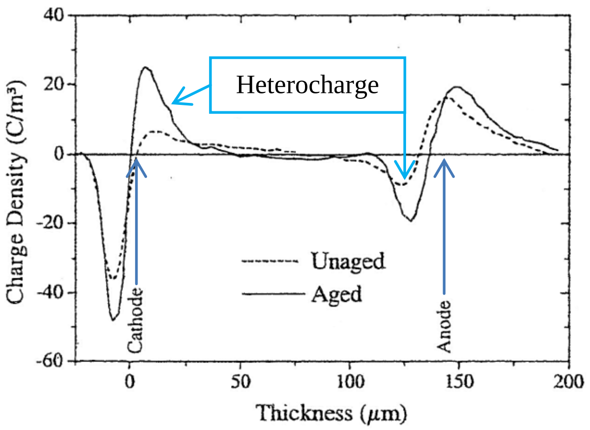
III. SPACE CHARGE MEASUREMENTS

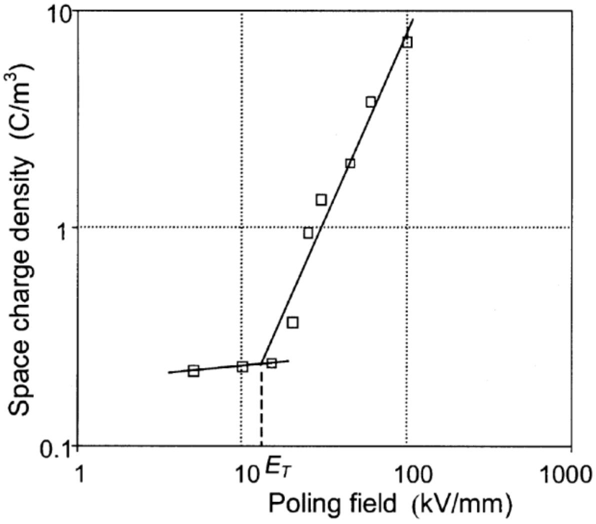
There are several methods for measuring space charge. Personally, I was very pleased to see developments in this area. The method to visualise space charge accumulation in extruded power cables when I started my career at STL Ltd. in 1984 was to cut a section from the cable and sprinkle the end with lycopodium powder. Whilst the effects could be quite pretty, the process was not very informative in terms of identifying space charge. The method was not quantitative, much of the charge accumulated due to the applied voltage had disappeared by the time the cable was cut, and the cutting itself introduced a considerable amount of triboelectric charge.

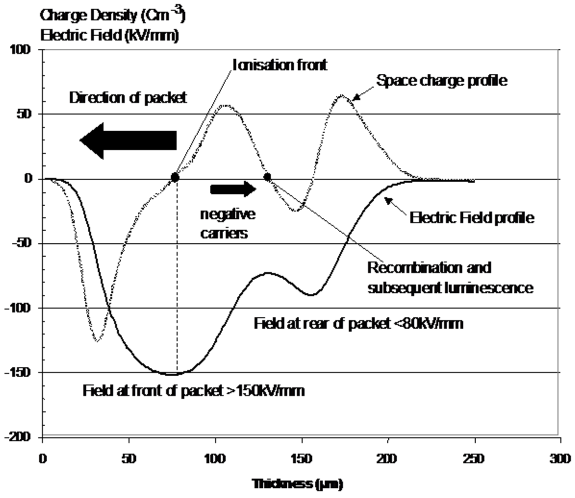
A. The Pulsed Electro-Acoustic (PEA) Technique

In 1985, Maeno *et al*, invented the pulsed electro-acoustic technique. This did not catch on fast since it required what were at the time difficult expensive electronics involving a pulse generator for repetitive high voltage (several kV) short (few nanosecond) pulses, a sensitive microwave amplifier, a high speed digital oscilloscope with a bandwidth of at least a GHz, and high-speed signal processing best done by a computer. It was also difficult to remove the electrical noise that masked the small signal and so the experimental technique was something of an art. However, by the mid 1990's all the electronics was much easier to acquire, although I recall that building our system in Leicester in the mid 1990's still cost around £100k in materials and components alone. The system was championed by Kaori Fukunaga, who I had the pleasure of hosting for a year as a research visitor at Leicester; her excellent English and carefully prepared presentations at many IEEE DEIS conferences meant that the PEA technique was adopted very widely. There was then something of a competition between the groups at Leicester and Southampton in the UK to produce a system that was fast enough to make measurements under AC conditions. We both managed this using complementary techniques, but there was not much to see; the DC effects were much more interesting.

The PEA technique is described in a book that Len Dissado and I edited containing papers presented at a conference organised by the Dielectrics Society at Canterbury in the UK [33]. The principle is reasonable straightforward, but the implementation is difficult. The technique measures space charge in a slab (usually a mm or so thick) or in a small cable although, as described below, we have now developed this for a full sized cable of any length. The measurement may be done whilst (or before or after) a voltage is applied to introduce space charge into the specimen. To detect the space charge, a short high voltage pulse is applied. The electrostatic field produced by this pulse causes charges within the dielectric to experience a momentary mechanical force. Since these charges are trapped and cannot move, the force is transferred to the bulk of the polymer and results in acoustic waves that travel







through the polymer towards the electrodes. Positive charges will be repelled by a positive pulse and so produce a compression wave that moves towards the negative electrode and a rarefaction wave that moves towards the positive electrode. The opposite will occur for negative charges. By sensing the acoustic wave, the time taken to reach the electrode after the pulse and the polarity of the acoustic wave it is possible to work out the polarity and position of the space charge in the dielectric. The pulse width must be much less that the time taken for the acoustic wave to travel through the specimen and the pulse voltage must be large enough to produce a decent acoustic signal. An acoustic delay, using a carefully machined slab of aluminium, is required to separate the electrical noise produced by the pulse from the tiny electrical signal produced by the piezoelectric sensor. The sensor thickness also dictates the spatial resolution of the system. A sensitive microwave amplifier next to the sensor with extremely carefully designed earthing systems are required to detect the signal. Signal averaging over several (or many) pulses are required to extract the signal from the noise. Rather complicated signal processing is then required to accurately deconvolve the space charge profile from the signal emanating from the piezoelectric transducer.

Complementary techniques can be used in which an acoustic signal is applied to the specimen and the corresponding electrical signal is detected. An example of this is the Laser Induced Pressure Pulse (LIPP) technique. Other pressure wave propagation techniques have been pioneered by Stéphane Holé in the laboratory of Jacques Lewiner in Paris [34]. My work in the area was supported by two grants from the EPSRC with Professor Robert Hill at King’s College London and utilised the expertise of John Alison, who has written an excellent article on the PEA technique [35]. (Robert had a great influence on my work as another co-worker of Len Dissado. He sadly passed away in 2011 after a long battle with Alzheimer's disease.)

Another non-destructive technique that is commonly used on power cables is the thermal step method (TSM). This has been championed by the group at Montpelier, France. A temperature step is applied to a short circuited insulating sample, such as a cable, and the capacitive current is measured; this is of the order of pA to nA. The current response can be related to the internal distribution of space charge. Either the inside or the outside of the cable can be heated; the outside has the advantage that a given length of cable can be studied. Testing under high voltage, DC cables can give significant current signals due to polarisation and conduction. A second “dummy” cable is then used, identical to the one under test, to enable the subtraction of these additional currents. An excellent introduction to the use of TSM for thick cables is contained in [36]. Its application to DC cables is described in [37].

IV. SPACE CHARGE MEASUREMENTS

There are numerous examples of space charge measurements and this area is in need of a careful review. For the purposes of this paper, I only give some examples of what can be measured that may be relevant to HVDC cables.

The first example is taken from one of my PhD students, Alex See, who was working on an EU project called ARTEMIS: Ageing and Reliability TEsting and Monitoring of power cables: diagnosis for Insulation Systems[4]. The cables investigated had a 1600 mm^2 copper conductor and a 26.6 mm thick XLPE insulation The cables were aged under a variety of fields and temperatures up to a maximum of 27.5 kV/mm and 95°C. Samples were prepared by peeling the cables and volatiles were removed using a thermal treatment. A typical result from a PEA measurement is shown in Fig. 12. The positions of the cathode and anode are marked by regions of negative and positive charge that were induced on these electrodes. Next to the electrodes, heterocharge is clearly seen, which has increased in the case of the aged cable. The work was complemented by other techniques including conduction and electroluminescence. The broad conclusion from this work was that ageing resulted in an increase in the concentration of shallow and deep trapping levels. Note that these are quite high levels of space charge density, but even these are caused by a small amount of charge. By this I mean that a charge density of 1 C/m^3 is roughly equivalent to the charges from only 6 electrons in a cubic micron of material. This would be comparable with the density of free charges found in a well-made undoped silicon wafer at room temperature.

Following the ARTEMIS project, Gian Carlo Montanari and others have suggested that a threshold voltage can be identified. Below this voltage, very little space charge accumulates, whereas above the threshold voltage space charge accumulates more rapidly. An example of this is shown in Fig. 13 from [38]. In order to support the concept of a threshold voltage for trapped space charge accumulation, it is noted that, whilst the insulation may exhibit ohmic behaviour at low voltages (i.e. at which the conduction current is proportional to the applied voltage), there is often a voltage above this at which the current rises more quickly, often as a power law. This "critical field" may correspond to the onset of space charge accumulation, but other conduction processes that do not involve space charge can also explain such non-linearities. Ref. [38] therefore explores the complementary techniques of space charge detection (using the PEA method) and electroluminescence. Three polymers: polyethylene, polyester and polycarbonate were investigated and in each polymer the threshold voltage found was independent of the technique used. This suggests that there is a physical basis for a threshold for trapped space charge accumulation. It is assumed that cable ageing would occur if this threshold was exceeded.

The final example I intend to give in this paper is a rather surprising result which occurs at very high fields in polyethylene, typically above about 60 kV/mm. Whilst it had always been assumed a steady state would eventually be reached if a DC voltage was applied, we found in the ARTEMIS project that "charge packets" could occur if a sufficiently high voltage was applied; we described these in [39, 40]. The first observation of such packets caused by space charge in a polymer under high voltage conditions was probably by Hozumi *et al* [41]. An example is shown in Fig. 14 and I hope to demonstrate this with a video at the conference. Again this is observed in a peeling taken from an XLPE cable. The peeling is 150 μm and the earthed side of the sample is found on the left hand side where the measured charge is negative. On the right there are two positive peaks. The right hand peak is the positive side (anode) and the middle positive peak is a moving 'charge packet'. This slowly moves from the right to the left, taking about 3 hours to cross this sample. A voltage of 18 kV was applied to the sample corresponding to an average electric field of 120 kV/mm. The actual electric field inside the sample is also shown in Fig. 14. In front of the packet the field has increased to over 150 kV/mm due to the effect of the space charge, but behind the packet the field is reduced to less than 80 kV/mm. It is thought that the very high electric field is enough to "rip" electrons off molecules causing them to ionise. The electrons then move by a conduction mechanism to the right, exposing the positively charged ions and generating the packet. Once the electrons encounter a smaller field at the back of the packet, they recombine with previously ionised molecules, and restore charge neutrality. This process repeats itself so, as the charge packet disappears into the grounded side of the specimen, a new charge packet emerges from the positive side.

More recently, Dissado *et al* [42] have reported on much faster smaller pulses crossing similar specimens, which they called "soliton-like". They ascribe this to a previously unknown conduction mechanisms which occurs at moderate fields (40-50 kV/mm). The charges move with a much higher mobility than would normally be found in such materials; the packets take about a second to cross the sample rather than the 3 hours seen previously. It is argued that the field mechanically bends the polymer molecule on which the charge is situated. The moves the charge towards the next polymer chain to which the charge is passed. This then causes the next chain to buckle and the charge is passed to the next chain, and so on. They describe this mechanism as follows: "… *a charged compression boundary is formed electro-mechanically during injection and thereafter travels as a coherent solitary wave (soliton) through the polymer.*" It is clear that high-field DC effects in polymer still have some surprises for us. It is possible that such high-field effects could be utilised to good effect.

V. CONDUCTIVITY MEASUREMENTS

The measurement of the dependence of conductivity upon temperature is clearly important for HVDC cables for the reasons explained in section II(B)(1) above. It would be desirable to have a low dependence of conductivity upon temperature, although this is generally not the case in polymers. It would also be also be desirable to have a high thermal conductivity. Indeed Pilgrim, Lewin and Vaughan from Southampton [43] have shown that, at least for AC cables, the properties offering the greatest improvement in ratings were the temperature limit and the thermal conductivity. Increasing the temperature limit would increase the Joule losses in the conductor but increasing the thermal conductivity would give a marked overall improvement even if at the expense of some other properties.

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[4] Contract number BRPR-CT98-0724, 1998-2002

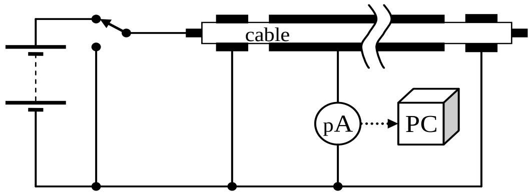

Fig. 15. Guard ring technique for measurement of low currents in a cable

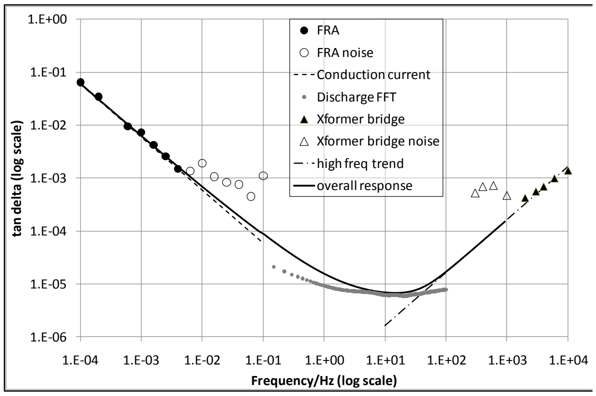

Fig. 16. Various measurements on a mini-cable system [44]. Note that, at low frequencies, the frequency response analyser (FRA) measurements demonstrate an inverse proporportionality to frequency and that they coincide with the conduction current measurements indicating that the latter is due to 'true conduction'.

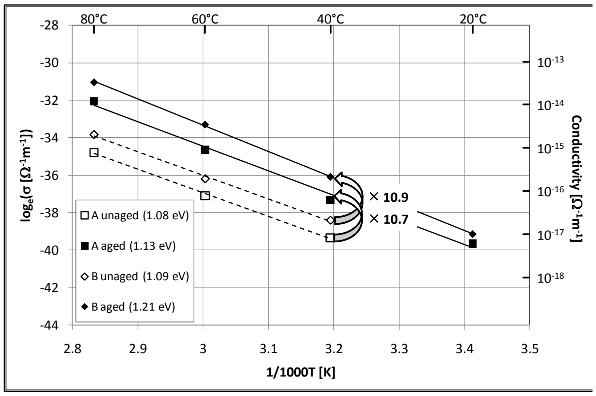

Fig. 17. Measurements of conductivty as a function of temperature for two XLPE variations for HVDC use [44] before and after themal ageing.

The measurement of conductivity should be fairly straightforward were it not for the very low currents that need to be measured. Guard ring techniques should be used (see Fig. 15) and indeed in [44] we found it very useful to make a zero-ripple 'HV' (1000 V) DC supply using 100 batteries in series. It may also be useful in determining the onset voltage for space charge accumulation (section IV), and it may be a marker for ageing [44, 45]. Because of polarisation currents, the effects of slight changes in temperature, etc., it is difficult to know whether a true conduction current is being measured. We have used techniques of both a guard ring direct measurement and a frequency response analyser (Fig. 16). At very low frequencies, if there is a true conductivity, then it is possible to show [44] that the imaginary part of the capacitance is inversely proportional to frequency and the real part is independent of frequency. At 20°C, the conductivity is extremely low: 10^{-17} $\mathrm{S.m^{-1}}$.

Fig. 17 shows typical conductivity measurements as a function of temperature [44]. It can be seen that the conductivity increases by a factor of 10 for a temperature rise approximately 20°C. Typically such materials are found to follow an Arrhenius law with an activation energy of around 1.1 eV. An interesting observation (which we have made on all cables that we have measured) is that the conductivity increases significantly – by about a factor of ten – after thermal ageing. This has also seen by other workers, e.g. [46]. The cables were obviously oxidised and the increase in conductivity may be due to the molecular bonds being weakened and an increase in free volume. This would lead to increases in the number and mobility of mobile charges.

At high electric fields, even before the onset of charge packet effects, the DC conductivity of many polymers is found to increase with electric field. An excellent discussion of this area [47] finds the use of a semi-empirical equation useful to describe this effect:

$$\sigma(E) = \sigma_0 e^{K|E|} \tag{3}$$

where $\sigma(E)$ is the conductivity as a function of field, and σ_0 and K are constants. The authors also note that ethylene – propylene rubber (EPR) and biaxially-oriented polypropylene (used for example in capacitors) both have a very low dependence on conductivity.

The relevance of this is twofold:

(i) Thermal breakdown may become the mechanism that limits the voltage of a given HVDC cable. In this breakdown mechanism the electrical power density into a region of the insulation (i.e. the product of the field and current density) is such that either the temperature increases above that which the insulation material can sustain without damage or that the electrical power into this region exceeds the rate at which it can be thermally conducted away and the temperature runs away. Fig. 10 shows that this happens at 340 kV for the particular cable under study.

(ii) It could be argued that some nonlinear increase in current with voltage is beneficial as high field points in the insulation lead to an increased conductivity, which reduces the local field. The maximum field in the insulation is therefore regulated. This is something that Brian Varlow (Manchester) had been pioneering with the addition of fillers for many years.

There therefore needs to be a careful balance between nonlinear effects on the one hand helping to reduce the probability of breakdown by ameliorating the effects of high-field producing cavities, protrusions and defects, whilst on the other hand leading to thermal breakdown.

VI. NANODIELECTRICS

Professor John Lewis from the University of Bangor, North Wales has long been interested in dielectric interfaces. In 1994 he wrote a seminal paper [49] on "Nanometric Dielectrics". In this paper he noted that very small particles – of the order of a few nanometres or 10's of nanometres – would have extremely high ratios of surface area to volume. The surface of such a particle incorporated into a polymer matrix would form an interface and have the potential to change the electrical properties of the material in this interface region. This region has become known as the "inter-phase" region or, more simply, the interaction zone. Lewis considered how this region might be changed using concepts of electrical double layers found in electrolytes such as the Stern and the Gouy-Chapman layers. These zones are likely to be more conductive than the surrounding polymer. A low concentration of nanoparticles may lead to the situation that nearly all of the polymer is occupied by overlapping interactions zones. For example, if the interaction zone thickness is 10 nm and the nanoparticles are spherical with a radius of 10 nm then with a concentration of only 4% (v/v), the interaction zones will overlap sufficiently to reach the percolation limit. Lewis has published a more detailed exposition of this area more recently [50].

In 2002, Keith Nelson joined me for a sabbatical in Leicester for a very productive six months where we (mainly he) formulated some "nanodielectrics" (to use the neologism coined by Michel Fréchette [51]). Looking back, these were very primitive and it is perhaps surprising that we got any good results at all. The host polymer used was epoxy resin as it was both something that we had a lot of experience with at Leicester and also a convenient material in which to mix particles. These could be added to the base resin before mixing in the hardener. We now know that the dispersion of particles is critical yet we obtained results by using a whisk made out of an electric drill! The ceramic nanoparticles were ~50 nm in diameter comprising alumina, titania, and barium titanate (AlO_2, TiO_2, and $BaTiO_3$). We compared the behaviour of these nanodielectrics with "microdielectrics" – containing similar particles but a few tens of microns in diameter. The preliminary results were published with excitement at the CEIDP at the end of that year [52]. We noted that, "*Very marked differences in charge accumulation are seen in filled materials depending on whether the filler has micron or nanometric dimensions*." Whereas the additions of microparticles result in significant heterocharge accumulation, the decay of space charge in the nanodielectrics was very rapid. Furthermore the dielectric response was very different. For example, the addition of the micro particles of TiO_2 to epoxy increased its relative permittivity. This is unsurprising, epoxy has a relative permittivity of around 4, whereas for TiO_2 this is around 92. However, when nanoparticles were added to the epoxy, its relative permittivity was reduced. This was such a surprising result that Keith is reputed to have bought a new dielectric spectrometer when he returned to the States as he had lost confidence in the equipment at Leicester. He found exactly the same results. The results are discussed in more detail in [53]. For a recent review of this area see the book edited by Keith Nelson [54].

Fig. 18 shows the field inside a low-density polyethylene (LDPE) 70 µm thick film with and without MgO nanoparticles 20 minutes after the application of 200 kV/mm [after 55]. The authors show that this is due to the accumulation of heterocharge near the negative terminal. Without the addition of nanoparticles, this heterocharge causes the internal field to double to 400 kV/mm. With nanoparticles, the field is almost uniform.

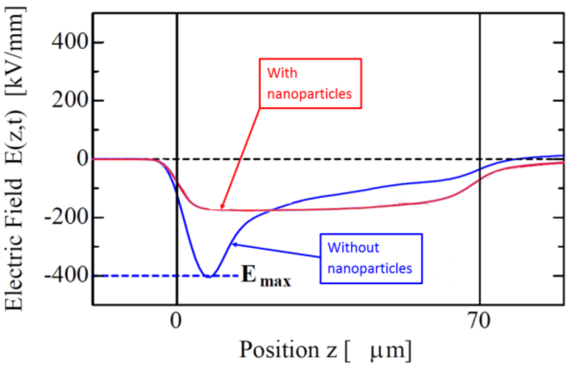

Fig. 18. The field inside a low-density polyethylene 70 µm thick film with and without MgO nanoparticles 20 minutes after the application of 200 kV/mm [after 55].

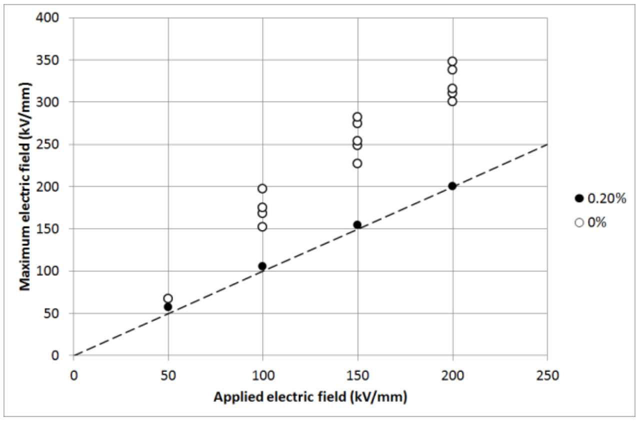

Fig. 19. Relationship between applied electric field and the maximum electric field in degassed XLPE samples with 0% and 0.2% filler content [56]

It was clear that the area had considerable promise for many applications including HVDC. The number of publications in this area has grown enormously since 2002, with many conferences holding dedicated sessions on nanodielectrics.

VII. INDUSTRIAL TAKE-UP

Various HVDC cable manufacturers have been incorporating nano-particles in an effort to reduce space charge. An example is that of the Japanese manufacturer, Viscas, who has been working with Tokyo City University and the National Institute of Information and Communications (NICT – who are experts in the PEA technique), in Japan. Their 2011 and 2013 Jicable papers [56, 57] describe XLPE cables with a conductive inorganic nano-filler for use up to 320 kV and 500 kV. The cable insulation is unusual in that it is black [58]. A PEA system was used to assess the internal space charge distributions. The papers show the development of space charge packets in the cables without the filler, there is no discernible increase in internal electric field up to an applied field of 200 kV/mm. Fig. 19 shows results based on data in [56] and it is clear that the effect of incorporating a small concentration of filler particles makes a huge difference in reducing the maximum internal field.

In the 2013 paper, a full-sized 320 kV HVDC XLPE cable is described which has been load cycle tested according to the CIGRÉ TB-496 pre-qualification test and type test. This includes a polarity reversal test in which a positive voltage of 1.4 U_0 is applied and the polarity reversed every four hours for the duration of the 10 cycles. The recommended time duration for a polarity reversal is 2 minutes. This is a particularly severe test for polymeric insulation in which space charge can accumulate since what might be homocharge (reducing the field near the conductor) becomes homocharge as the polarity is revered and the resulting internal fields can be very high. It is therefore particularly good that the cable not only survives this test but has no discernible accumulation of space charge.

One of my final projects, before I left the University of Leicester, was working with Alstom Grid, who were interesting in bidding for turnkey HVDC projects. Whilst they had a lot of experience in the power converters, they did not possess a cable manufacturing facility and therefore needed to have the facilities to select cables. As a consequence of this project, they now have an HVDC cable ageing facility, Fig. 20. This has the capability to house two temperature-controlled cables operating at full DC voltage. The cable can be simultaneously tested for space charge using both the PEA and TSM methods (which, to my knowledge, has not been done before) and the conduction and low frequency dielectric responses can be established. The PEA, Fig. 21, operates on a full-sized cable (for example with 20 mm thick insulation) and can work at a high temperature to provide the desired temperature gradient.


Fig. 20. HVDC cable ageing facility at Alstom Grid, Stafford, UK

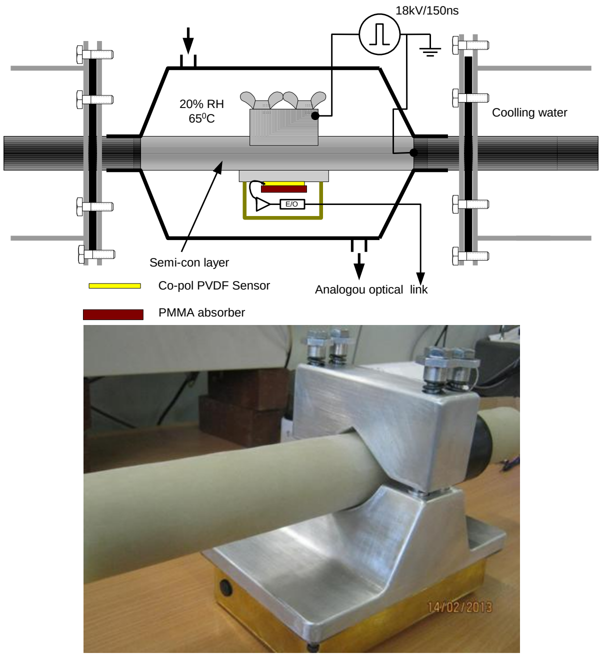

Fig. 21. PEA space charge measurement system in the above facility.

VIII. CONCLUSIONS

Extruded cables have become the *de facto* standard for MV and HV AC cables. The early problems associated with water and electrical treeing have been largely overcome and the failure rates due to ageing of such systems a much lower than due to external factors which often involve anchors or digging machines. Whilst treeing problems may not be such a problem in HVDC extruded cables, their introduction requires attention in controlling internal fields, which are affected by changes of conductivity due to temperature changes and by space charge accumulation. Techniques have been developed to measure both conductivity and space charge in such systems. Nanodielectrics may offer the key to controlling these factors in the polymeric insulation of HVDC cables. There is now a lot of activity in developing manufacturing of HVDC extruded cables. The applications are plentiful in our new greener world. I am pleased to have played a small part in this development.

ACKNOWLEDGMENT

I would like to acknowledge the help of the many colleagues and PhD students, many of whom are listed in the references below, for their friendship over many years and the fruitful working relationships we have developed.

REFERENCES

[1] G. Mazzanti and M. Marzinotto, Extruded Cables for High-Voltage Direct-Current Transmission, John Wiley & Sons, 2013

[2] e.g. ABB, "Three Gorges, China", http://tinyurl.com/ABB3gorges, retrieved 27 March 2014

[3] e.g. Campaign to Protect Rural England, "Little ambition to underground power lines" http://www.cpre.org.uk/media-centre/news-release-archive/item/2978-little-ambition-to-underground-power-lines, 16 July 2012, accessed 27 March 2014

[4] Parsons Brinckerhoff Electricity Transmission Costing Study, 31 January 2012 (available at http://tinyurl.com/costing-study, accessed 29 March 20140

[5] H. Orton, History of Underground Power Cables, IEEE Electrical Insulation Magazine, Vol. 29, No. 4, pp 52-57, July/August 2013

[6] J. Densley, Ageing and diagnostics in extruded insulations for power cables, Proceedings of the 1995 IEEE 5th International Conference on Conduction and Breakdown in Solid Dielectrics, 1995. ICSD'95., pp. 1 – 15, 1995

[7] N. Hampton, R. Hartlein, H. Lennartsson, H. Orton, and R. Ramachandran, Long-life XLPE Insulated Power Cable, Jicable'07, paper: 2007-C5-1-5, 2007 (available at https://smartech.gatech.edu/handle/1853/27815)

[8] J.Z. Hansen, Results from Danish failure statistics for medium voltage XLPE cables, 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Page(s): 1 – 4, 2013

[9] L.A. Dissado, J.C. Fothergill and S.V. Wolfe, Mechanisms and measurement of water tree growth, Proceedings of the 1st. IEEE International Conference on Conduction and Breakdown in Solid Dielectrics, Toulouse, 250-254, 4-8 July 1983

[10] Dissado, J.C. Fothergill and S.V. Wolfe, Preliminary investigation into treeing, morphology and the electrical properties of polymers, Annual Report Conference on Electrical Insulation and Dielectric Phenomena, p 264-277, 1981

[11] L.A. Dissado, J.C. Fothergill and S.V. Wolfe, Développements récents dans l'étude du polyéthylène réticule destine à l'isolation des câbles d'énergie, Revue des Télécommunications, ITT, Vol. 57, No. 2, pp87-90, 1982

[12] M.T. Shaw and S.H. Shaw, Water Treeing in Solid Dielectrics, IEEE Transactions on Electrical Insulation, Volume: EI-19 , Issue: 5, pp 419 – 452, 1984

[13] e.g. H. H. Sæternes, J. Aakervik and S. Hvidsten, Water Treeing in XLPE Insulation at a Combined DC and High Frequency AC Stress, IEEE Electrical Insulation Conference, pp 495-498, June 2013

[14] L.A. Dissado, and J.C. Fothergill, Electrical Degradation and Breakdown in Polymers, Peter Peregrinus Ltd. for the IEE, 1992, ISBN 0 86341 196 7

[15] J.V. Champion, S.J. Dodd, and G.C. Stevens, Quantitative determination of the residual mechanical stress and its relaxation in synthetic resin with an embedded electrode, Journal of Physics D: Applied Physics, v 25, n 12, p 1821-1824, Dec 14 1992

[16] J.V. Champion, S.J. Dodd, and G.C. Stevens, Quantitative measurement of light emission during the early stages of electrical breakdown in epoxy and unsaturated polyester resins, Journal of Physics D: Applied Physics, v 26, n 5, p 819-828, May 14 1993

[17] J.V. Champion, S.J. Dodd, and G.C. Stevens, Long-term light emission measurement and imaging during the early stages of electrical μbreakdown in epoxy resin, Journal of Physics D: Applied Physics, v 27, n 3, p 604-610, Mar 14 1994

[18] J.V. Champion, S.J. Dodd, and G.C. Stevens, Analysis and modelling of electrical tree growth in synthetic resins over a wide range of stressing voltage, Journal of Physics D: Applied Physics, v 27, n 5, p 1020-1030, May 14 1994

[19] J.C. Fothergill, L.A. Dissado, and P.J.J. Sweeney, Discharge-avalanche theory for the propagation of electrical trees a physical basis for their voltage dependence, IEEE Transactions on Dielectrics and Electrical Insulation, v 1, n 3, p 474-486, Jun 1994

[20] S.J. Dodd, N. Chalashkanov, and J.C. Fothergill, Statistical analysis of partial discharges from electrical trees grown in a flexible epoxy resin, Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP, p 666-669, 2008

[21] S.J. Dodd, N. Chalashkanov, J.C. Fothergill and L.A. Dissado, Influence of the temperature on the dielectric properties of epoxy resins, Proceedings of the 2010 IEEE International Conference on Solid Dielectrics, 2010

[22] S.J. Dodd, N. Chalashkanov, and J.C. Fothergill, Partial discharge patterns in conducting and non-conducting electrical trees, Proceedings of the 2010 IEEE International Conference on Solid Dielectrics, 2010

[23] S.J. Dodd, N. Chalashkanov, L.A. Dissado and J.C. Fothergill, Pulse sequence analysis on PD data from electrical trees in flexible epoxy resins, Annual Report - Conference on Electrical Insulation and Dielectric Phenomena, CEIDP, p 776-779, 2011

[24] F. Noto and N. Yoshimura, "Voltage and Frequency Dependence of Tree Growth in Polyethylene", Ann. Rep. CEIDP, pp. 207-217, 1974

[25] R. J. Densley, "An Investigation into the Growth of Electrical Trees in XLPE Cable Insulation", IEEE Trans. Electr. Insul., Vol. 14, pp. 148-158, 1979

[26] e.g. L. Ying and C. Xiaolong, Electrical Tree Initiation in XLPE Cable Insulation by Application of DC and Impulse Voltage, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 20, No. 5; pp. 1691 to 1698, October 2013

[27] P. H. F. Morshuis and J. J. Smit, Partial Discharges at dc Voltage: Their Mechanism, Detection and Analysis, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 12, No. 2; 328 – 349, April 2005

[28] M. J. P. Jeroense and P. H. F. Morshuis, "Electric fields in HVDC paper-insulated cables", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 5 No. 2, pp. 225-236, April 1998

[29] Tong Liu , Dielectric Spectroscopy of Very Low Loss Model Power Cables, Thesis submitted for the degree of Doctor of Philosophy at the University of Leicester, UK, February 2010

[30] M. Meunier, N. Quirke, N. and A. Aslanides, Characterisation of charge carrier traps in polymeric insulators, Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp 21 - 24 2000

[31] M. Meunier and N. Quirke, Molecular modeling of electron trapping in polymer insulators, Journal of Chemical Physics, v 113, n 1, p 369-376, Jul 2000

[32] T. Maeno, H. Kushibe, and T. Takada, "Pulsed Electro-Acoustic Method for the Measurement of Volume Charges in E-Beam Irradiated PMMA," CEIDP Ann. Rep., pp. 389-397, 1985

[33] Fothergill, J.C. & Dissado, L.A. (eds.): *Space Charge in Solid Dielectrics*, The Dielectrics Society, ISBN: 0 9533538 0 X, 1998

[34] J. Lewiner, S. Holé, and T. Ditchi, Pressure wave propagation methods: A rich history and a bright future. IEEE Transactions on Dielectrics and Electrical Insulation, v 12, n 1, p 114-126, February 2005

[35] J. Alison, High field pulsed electro-acoustic apparatus for space charge and external circuit current measurement within solid insulators, Measurement Science and Technology, v 9, n 10, p 1737-1750, Oct 1998

[36] J. Castellon, P, Notingher, S. Agnel, A. Toureille, F. Brame, P. Mirebeau, J. Matallana, Electric field and space charge measurements in thick power cable insulation, IEEE Electrical Insulation Magazine, Volume: 25, Issue: 3, Page(s): 30 – 42, 2009

[37] P. Notingher, Jr., S. Agnel, and A. Toureille, "Thermal step method for space charge measurements under applied dc field," IEEE Trans. Dielectr. Electr. Insul., vol. 8, no. 6, pp. 985–994, 2001.

[38] L. A. Dissado, C. Laurent, G. C. Montanari, and P. H. F. Morshuis, "Demonstrating a Threshold for Trapped Space Charge Accumulation in Solid Dielectrics", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 12, No. 3; 612-620, June 2005

[39] A. See, L.A. Dissado, J.C. Fothergill, G. Teyssedre, C. Laurent, G.C. Montanari, F. Palmieri, "The relationship between charge distribution, charge packet formation and electroluminescence in XLPE under DC" Proceedings of the 2001 IEEE 7th International Conference onSolid Dielectrics, 97 - 100, 2001

[40] A. See, L. A. Dissado and J. C. Fothergill, "Electric field criteria for charge packet ... movement in XLPE", IEEE Trans. Diel. Elect. Insul., Vol. 8, pp. 859-865, 2001

[41] N. Hozumi, H. Suzuki, T. Okamoto, K. Watanabe, A. Watanabe, "Direct observation of time-dependent space charge profiles in XLPE cable under high electric fields", IEEE Transactions on Dielectrics and Electrical Insulation, v 1, n 6, p 1068-1076, Dec 1994

[42] L.A. Dissado, G.C. Montanari, D. Fabiani, D., "Fast soliton-like charge pulses in insulating polymers", Journal of Applied Physics, Volume 109, Issue 6, pp. 064104-064104-9, 2011

[43] J.A. Pilgrim, P.L. Lewin and A.S. Vaughan, "Quantifying the Operational Benefits of New HV Cable Systems in terms of Dielectric Design Parameters", Conference Record of the 2012 IEEE International Symposium on Electrical Insulation (ISEI), 261 – 265, 10-13 June 2012

[44] J. C. Fothergill; Tong Liu; S. J. Dodd; L.A. Dissado; U.H. Nilsson, "The Measurement of Very Low Conductivity and Dielectric Loss in XLPE Cables: A Possible Method to Detect Degradation due to Thermal Aging" IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 18, Issue 5, pp. 1544-1553, October 2011

[45] J.C. Fothergill, G.C. Montanari, G.C. Stevens, C. Laurent, G. Teyssedre, L.A. Dissado, U.H. Nilsson, and G. Platbrood, "Electrical, Microstructural, Physical and Chemical Characterization of HV XLPE Cable Peeling for an Electrical Aging Diagnostic Data Base", IEEE Transactions on Dielectrics and Electrical Insulation, v 10, n 3, p 514-527 June 2003

[46] M. Nedjar, "Effect of thermal aging on the electrical properties of crosslinked polyethylene", J. Appl. Polym. Sci., Vol. 111, pp. 1985-1990, 2009.

[47] X. Qi, Z. Zheng, Z. S. Boggs, “Engineering with nonlinear dielectrics”, IEEE Electrical Insulation Magazine, Volume: 20 , Issue: 6, 27 – 34, 2004

[48] B.R. Varlow, J. Robertson, K.P. Donnelly, “Nonlinear fillers in electrical insulating materials” IET Science, Measurement & Technology, Volume: 1 , Issue: 2, 96 – 102, 2007

[49] Lewis, T. J., “Nanometric Dielectrics”, IEEE Trans on Diel. and Elect. Ins., Vol.1, 1994, pp 812-25

[50] T. J. Lewis, “Interfaces are the dominant feature of dielectrics at the nanometric level”, IEEE Trans. Dielectr. Insul., vol. 11, pp. 739-753, 2004.

[51] M.F. Fréchette, M. Trudeau, H.D. Alamdari and S. Boily, “Introductory remarks on nanodielectrics,” Proc. IEEE Conf. on Elect. Insul. and Dielec. Pheno., Kitchener, Ontario, Canada, Oct. 14-17, 2001.

[52] J.K. Nelson, J.C. Fothergill, L.A. Dissado, W. Peasgood, “Towards an understanding of nanometric dielectrics, Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Annual Report, p 295 298, 2002

[53] J.K. Nelson and J.C. Fothergill, “Internal charge behaviour of nanocomposites”, Nanotechnology, volume 15, issue 5, p 586 – 595, 2004

[54] John Fothergill, “Electrical Properties”, Chapter 7 of “Dielectric Polymer Nanocomposites” (ed. J K Nelson) Springer 2010, pp.197-228

[55] T. Takada, Y. Hayase, Y. Tanaka, Y and T. Okamoto, “Space charge trapping in electrical potential well caused by permanent and induced dipoles for LDPE/MgO nanocomposite” IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 15 , Issue: 1, 152 – 160, 2008

[56] T. Mizuno, T. Takahashi, H. Harada, N. Hayashi, Y. Tanaka, T. Maeno, “Effect of Conductive Inorganic Filler on Space Charge Characteristics in XLPE as a HVDC Insulating Material” Paper c.5.2, Jicable’11, 2011

[57] H. Mori, H. Niinobe, Y. Yagi “Space charge measurements and characteristics of HVDC XLPE cable” paper P05, Jicable HVDC’13, 2013

[58] http://www.pesicc.org/iccwebsite/subcommittees/G/Presentations/2011S Sprin/DevelopmentofHVDC.pdf, accessed April 1, 2014