Electrical Treeing in Low-density Polyethylene in DC fields and under DC Stresses Superimposed with AC ripples

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List of Abbreviations

2D: Two-dimensional

3D: Three-dimensional

AC: Alternate Current

AFM-IR: Atomic Force Microscope-Infrared Spectroscopy

CCD: Charge-coupled Device

DC: Direct Current

EL: electroluminescence

ESR: Electron Spin Resonance

FTIR: Fourier-Transform Infrared Spectroscopy

GDP: Gross Domestic Product

HFCT: High Frequency Current Transformer

HVDC: High-voltage Direct Current

IGBT: Insulated Gate Bipolar Transistor

LDPE: Low-density polyethylene

PD: Partial Discharge

PRPD: Phase-resolved Partial Discharge

PSA (Pulse Sequence Analysis)
PTFE: Polytetrafluoroethylene

PWM: Pulse Width Modulation

RMS: Root Mean Square

RMSE: Root Mean Squared Error

SBFSEM: Serial Block-face Scanning Electron Microscopy

SEM: Scanning Electron Microscopy

SGCC: State Grid Corporation of China

TEM: Transmission Electron Microscopy

UHVDC: Ultra-high-voltage Direct Current

UV: Ultraviolet

VSC: Voltage Sourced Converter

XCT: X-ray Computed Tomography

XLPE: Cross-linked Polyethylene
Abstract

HVDC transmission is playing a critical role in modern societies with the development of electricity generation from renewable energy worldwide. Electrical treeing is one type of long-term ageing in polymeric insulation and will eventually lead to insulation failure. While it has been intensively investigated in AC fields, very limited research has been conducted on treeing in DC fields and in superimposition fields which can well represent the working conditions in HVDC networks, i.e., a higher DC component with AC ripples. This work researched treeing in low-density polyethylene with a typical needle-plane geometry. It began with the effect of the interface between the metallic needle and the polymer on treeing in AC fields, and then investigated initiation and growth under DC stresses in both polarities (+DC and -DC hereafter) and under DC stresses superimposed with AC ripples (+DC plus AC ripples and -DC plus AC ripples hereafter).

Optically invisible air gaps of 10-55 µm in height had a possibility to form naturally at the metal-polymer interfaces and affected initiation and the subsequent growth in AC fields. Under +DC, tree initiation lengths, were at least one order of magnitude longer than in AC fields and the initiation voltage was close to the short-time local breakdown voltage. While it was difficult to employ PDs as treeing indicators under +DC, under +DC plus AC ripples differences in PD phase distribution and PD energy were found between samples with and without trees. Under -DC, tree initiation occurred over a wider range of voltage magnitudes within a shorter time and had a shorter initiation length than under +DC. Considerable step-like length propagation was seen shortly after initiation. PDs could be measured prior to tree initiation and a comb-like appearance in the PD magnitude variation trend was seen during treeing, however, it did not form PD clusters. Under -DC plus AC ripples, a slim bouquet tree structure which was short in length and narrow in width developed. In 2D projections, channels covered all of pixels of the treeing area; in 3D XCT reconstructions well-interconnected islands are apparent and its 3D fractal dimension, was much larger than its 2D equivalent. PDs had combined characteristics of negative DC and AC fields, i.e., comb-like appearance with a wing-like PRPD pattern, as well as its own features. Further fine channels developed from the existing tree structure while the DC source was ramping down, with and without an AC voltage superimposed onto -DC and regardless of the length and treeing area of the existing structure.

These phenomena are explained in terms of space charge injection and accumulation with polarity effects due to the differences in nature between holes and electrons.
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Chapter 1 Introduction

The background of the project *Electrical Treeing in Polymeric Insulation in DC fields and under DC stresses Superimposed with AC Ripples* and a brief introduction to electrical treeing are presented in this chapter, focusing on the development of the renewable energy market worldwide, and the need to decrease transmission losses and overcome transmission distance limits using HVDC (high-voltage direct current). The objectives, methodology and outline of this thesis are also presented, and main contributions summarised.

1.1 Background

1.1.1 Development of Renewable Energy

Recent decades have seen a steady increasing trend in both energy consumption and electricity generation from renewable energy across the world. According to the latest statistical review of world energy published by BP [1], despite the fact that the GDP rise was modest in 2018, global primary energy consumption increased by 2.9% in the same year, the largest growth since 2010 and twice its 10-year average. Along with energy use carbon emissions grew by 2.0%. It was also the biggest rise for seven years and put pressure on the UN’s 2050 Carbon Neutrality goal, which refers to net-zero carbon dioxide emissions by cutting emissions as close to zero as possible and reabsorbing those that cannot be cut such as from living creatures [2][3]. However, there was good news in the power sector which is the largest contributor to carbon emissions in the energy system. Regarding electricity generation growth, the leading rise of 14.5% was made by renewable energy, accounting for approximately a third of the whole growth. By country, China remained the largest growing market in renewable energy. As is shown in Figure 1-1, renewables are the only electricity generation source which has kept rising constantly since 2000, and renewables share rose from only 3% globally in 2008 to 9.3% in 2018, with Europe at the top with 18.7%. It should be noted that renewables plotted
in Figure 1-1(b) mainly included wind and solar energy and excluded hydropower, which is also considered as renewable energy but was developed much earlier and now has a steady share of electricity generation as shown by the blue curve in Figure 1-1(a).

![Figure 1-1 Share of electricity generation a) globally by fuel types and b) from renewables by region [1]](image)

In Europe, the UK owns the world’s largest offshore windfarm, The London Array, with 175 turbines in total and overall capacity of 630 MW, which started commercial operation in 2012 and provides electricity to over 560 thousand UK homes per year [4]. The UK also has the world’s biggest offshore windfarm under development, Dogger Bank, which has obtained permission for 400 turbine installation and will be responsible for 2.5% of electricity needs in the UK when completed [5]. Offshore windfarms are also a key form of renewable energy for the Netherlands. The Dutch central government aimed for the goal that a minimum of 27% of all energy used within the Netherlands would be sustainable by the year 2030, when offshore windfarms will generate approximately 11 GW and supply 8.5% of all the energy within the country [6]. In Germany solar energy or the photovoltaic system in electricity generation has been rising for decades and saw an annual increase of 16% in 2018, which topped the power generation types listed in Figure 1-2 and was almost triple the increase in wind energy [7].
1.1.2 Application of HVDC in Power Transmission

While clean electricity generation is one thing, efficiently transmitting it over long distances, such as between neighbouring countries or between different parts within a large country, is another. AC is the traditional way to transmitting electricity whereas HVDC transmission has many advantages with which AC can never compare. For example, when AC systems are to be connected, they must be synchronised, meaning at the same voltage magnitude, frequency, and phase. However, HVDC enables secure and stable asynchronous interconnection of power networks that operate on different frequencies. A typical HVDC transmission network consists of 1) DC links which can be cables or overhead lines, 2) two power converters, one converting AC to DC and the other vice versa, and 3) filters and reactors to achieve good power quality. Figure 1-3 displays a typical diagram of HVDC network linking two asynchronous AC systems [8]. Moreover, unlike AC transmission where the reactive power flow due to the large cable capacitance or overhead line capacitance will limit the maximum possible transmission distance, there is no such limitation with HVDC. Other advantages of HVDC include, but are not limited to, 1) short-circuit capacity remains unchanged (therefore no need in upgrading protection measures and equipment), 2) precise control of power flow, 3) no Ferranti effect when open circuited or when there is a low load [9], and 4) no alternating electro-magnetic fields (therefore less environmental impact) [10]. On the other hand, despite many advantages there are limitations in HVDC systems. For instance, DC
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Converter stations are more complex and expensive than AC substations [10]. Furthermore, electronic semiconductor valves, the core part in power converters, are known to be the source of unwanted harmonics which are transferred into the DC side in power transmission networks [11]. It is not surprising that AC ripples exist along with DC networks in insulation systems in service. This is why DC stresses superimposed with AC ripples was included in this project. AC harmonic filters (item 2 in Figure 1-3) causing considerable overvoltage during faulty recovery is another limitation in HVDC applications [10]. Deciding between AC and HVDC transmission is a complicated subject which requires overall consideration of multiple factors, and HVDC is playing a role with increasing importance in modern societies.

For offshore wind connections, for example Dogger Bank mentioned above, HVDC links are a more competitive technical alternative to the traditional AC transmission from the perspective of investment and operational cost [12]. The state-of-the-art HVDC Light® technology, the latest HVDC technology employing PWM (pulse width modulation) and semiconductor valves such as IGBTs (insulated gate bipolar transistors) to build VSCs (voltage source converters) in order to achieve a precisely controllable and visually compact converter design [13], will be used in this project with voltages of ±320 kV and it will be the first ever use of the HVDC technology in the UK’s offshore windfarms [14]. HVDC technology is also the best solution in grid links over long distances given that AC transmission has a distance limit due to reactive power flow. The 580 km long NorNed
Link at ± 450 kV running between Feda and Eemshaven was completed in 2008 and connected the hydropower in Norway and the wind power in the Netherlands [15]. Nordlink is Europe’s longest HVDC interconnection and consists of 516 km long submarine cables and 54 km long land cables, connecting hydropower in Norway to Germany [16]. The North Sea Link (NSL) is another example of HVDC use in interconnecting grids. The 730 km long NSL at ± 525 kV is the world’s longest subsea link, completed in 2021, and connects Norway and the UK [17]. It increases the security of power supply for both countries by balancing the energy flow between hydropower in Norway and windfarms in the UK at different times with different energy demands. HVDC Light® technology has been used, as in the projects NordLink and Dogger Bank.

Besides for successfully installed subsea links, underground HVDC transmission is also of great importance on land considering the public acceptance of overhead power lines is relatively low [18]. The biggest demand for HVDC links on land is perhaps in Germany and China. In Germany the officially confirmed plan of HVDC transmission corridors for 2025 estimated a total length of 3200 km from North to South within the country, with a total transmission capacity of 10 GW [19]. In geographically enormous China there is an urgent need to bring the electricity generated from renewable energy in its Interior to its Eastern Coast, which occupies 10% of China’s territory but is home to 38% of the population and creates about half of the GDP. To tackle this challenge, State Grid Corporation of China (SGCC) has been working on UHVDC (ultra-high-voltage direct current), which refers to ±800 kV and above, since 2004. By June 2019 there had been 10 UHVDC transmission links shown in Figure 1-4, with a total capacity of 296.2 GW in operation run by SGCC [20]. Furthermore, China’s the Belt and Road Initiative, a transcontinental infrastructure project which will link China and East Asia to Europe [21], includes a long-term goal of energy corridors interconnecting grids between China and Europe [18]. All these push HVDC power transmission systems to a record level and a continuous increase in (U)HVDC applications is predicted in the foreseeable future worldwide.
1.1.3 Electrical Treeing in Polymeric Insulation

Insulation systems of many varieties, including cable insulation, overhead line insulators, bushings, and switchgear, play a critical role in the reliability of power transmission at high voltages. Electrical treeing is one type of long-term degradation in polymeric insulation, featuring in tree-like channels [22] as shown in Figure 1-5(a). These form in polymers when there exists a high and divergent electric field. It is also well known as precursor to the total breakdown of insulation [23], as shown in Figure 1-5(b) which displays cable failure by electrical trees bridging the insulation thickness, therefore determining its lifetime. For cable insulation, electrical trees are usually found to start at the regions of electric field enhancement, such as semiconducting/conducting contaminants protruding into the polymeric insulation and structural irregularities in the polymer itself. Once tree channels form, they will lead to local or eventually global breakdown.

Electrical trees have been studied by many researchers for many years [24]. In laboratory tests, a metallic needle tip is most commonly employed to form the geometry needed to generate the local electrical field stress when high voltage is applied to the needle. Commercial needles with good quality control allow the reproducibility of geometry during tests with various stress conditions, facilitating comparisons of
experimental results and further analysis later. Electrical trees are usually classified into three types of shape: branch-shaped, bush-shaped and bush-branch-shaped [24], all of which are illustrated in Figure 1-6. A structure with one or more branched channels is the signature of branch-shaped trees; bush-shaped trees exhibit densely packed channels which appear to be the botanical tree termed bush; bush-branch-shaped structure is a variant of bushed structure with branches further growing from the bush-shaped boundary.

Figure 1-5 Electrical trees a) in extruded cable insulation [22] and b) through the total insulation [23]

Figure 1-6 Three typical types of electrical trees in polymers (under laboratory conditions)

The process of electrical treeing is often distinguished as a three-stage one: inception, propagation and runaway [24]. The schematic representation of typical electrical tree growth is shown in Figure 1-7. The inception stage features an inception or initiation time defined as the period in which an observable tree of typically ~10 µm in length...
forms after voltage application. During the propagation stage the growth rate usually exhibits a fast-then-slow trend, followed by the runaway stage which will eventually result in electrical failure: total breakdown of the insulation.

![Figure 1-7 Schematic representation of typical electrical treeing process [24]](image)

However, all these conclusions are concluded mainly from research under AC stresses and much less is known for DC networks, which is the only viable option for long-distance power transmission or grid links in today’s global energy markets. Moreover, engineering of DC insulation is also largely based on the experience from previous AC networks. Therefore, it is of great necessity to further investigate ageing phenomena and long-term reliability of polymeric insulation in HVDC transmission systems.

### 1.2 Objectives

The overall aim of this research is to investigate electrical tree initiation and growth in polymers in DC fields and under DC stresses superimposed with AC ripples to further knowledge of electrical treeing and hopefully assist with the design of DC transmission networks.
The specific objectives are as follows,

- To design a circuit to superimpose AC ripples onto high voltage DC source in a controllable way.
- To develop PD measurements with good balance between acceptable background noise and ‘clean’ PD data including both PD magnitude and phase information for further off-line analysis.
- To fabricate electrically strong treeing samples to withstand high voltage DC with good sample transparency for optical observation.
- To quantitatively determine the sample quality in terms of unwanted defects and investigate the effect of sample fabrication procedure on treeing.
- To initiate and grow electrical trees under ± DC stresses and under high voltage DC stress in presence of AC ripples and record accompanying PD signals.
- To three-dimensionally image electrical trees grown under high voltage DC stress in presence of AC ripples.
- To analysis the role of space charge and develop models of tree initiation and growth under DC stress and under DC stress in presence of AC ripples.

1.3 Methodology

The typical needle-plane geometry for electrical treeing was employed in this research. Low density polyethylene (LDPE), the base polymer of commercial XLPE cables, was chosen to fabricate treeing samples. Epoxy resin samples were also used to test the circuit performance such as PD background noise, as previous experience shows that epoxy resin treeing samples have stronger electrical strength than LDPE ones. The condition of the needle tip after insertion into a LDPE slab was scanned by Micro-XCT (X-ray Computed Tomography) equipment and 2D radiography was captured. The superimposition of high voltage DC and AC ripples was obtained using a Glassman ± 100 kV DC source and a Trek HV amplifier as the AC source. Optical images of trees were taken by a powerful CCD camera. The magnitude and reference phase of PD signals were
measured by use of two sets of commercial products: a high-frequency current transformer (HFCT), a coupling device and Omicron® MPD 600. Micro-XCT was also employed for 3D imaging after tree growth.

1.4 Main Contributions

This research makes the main contributions as follows,

- The superimposition of high voltage DC and AC ripples was achieved in a controllable way with PD measurement of a good sensitivity.
- Sample quality in terms of natural but unwanted defects around the needle tip was presented quantitatively. Air gaps of 10-55 µm in height, which are usually optically invisible, could form naturally in LDPE samples and affected tree initiation and the subsequent growth in AC fields.
- Electrical treeing was investigated under DC stresses in both polarities. It is argued that electron injection in negative DC fields played a more pronounced role and led to more complicated phenomena than hole injection in positive DC fields.
- Electrical treeing was investigated under very high voltage DC stress in presence of AC ripples (+45 kV plus 5 kV pk and -60 kV plus 7 kV pk) to better represent working conditions of cables in DC networks.
- A small AC ripple (5 kV pk) superimposed onto positive DC initiation voltage had the chance of resulting in catastrophic failure to insulation, highlighting the importance of good power quality in positive HVDC networks in a long run.
- A distinguishing tree structure was identified under negative DC superimposed with AC ripples and named ‘slim bouquet’ and its 3D imaging revealed that $^{3d}Df$ was a better tool to describe such a dense structure.
- Further fine channel development from the existing tree structure during DC ramp down was observed under negative DC superimposed with AC ripples and a dynamic model of space charge distribution was proposed to explain it.
The understanding in space charge injection and accumulation and the knowledge of electrical ageing in DC and AC superimposition fields are furthered by consideration of the treeing behaviour in terms of tree initiation, tree growth, morphology, and partial discharges.

1.5 Thesis Outline

This thesis is organised into six chapters as follows,

Chapter 1: Introduction

This chapter gives a brief introduction of development of renewable energy in the world’s energy market and HVDC application in power transmission globally, followed by the importance of the research on electrical treeing in polymers under close-to-real conditions of polymeric insulation in service. The objectives and methodology are also stated.

Chapter 2: Literature Review

This chapter reviews key literature on important phenomena in treeing, theories on tree initiation, electrical tree growth and the effect of gas phase between needle and polymer on electrical treeing, including the collaborative output with Dr. Hualong Zheng in the early stage of this project of the effect of the metal-polymer interface on treeing in pure AC fields. All are relevant knowledge involved in this research. Critical opinions upon the literature are also given.

Chapter 3: Experimental Description

This chapter describes all the experimental work involved in this project. It begins with sample fabrication and defect detection by Micro-XCT, followed by exploration in superimposition of a high DC voltage and AC ripples with PD measurement and 3D imaging principles, and ends with test arrangements.
Chapter 4: Treeing in Positive DC Fields and under Positive DC Superimposed with AC Ripples

This chapter introduces and discusses the test results in positive DC fields and under positive DC superimposed with AC ripples. Different phenomena of tree initiation and growth and PD activity occur in cases with high positive DC voltages involved compared with in AC fields. Explanations for these phenomena are presented.

Chapter 5: Treeing in Negative DC Fields and under Negative DC Superimposed with AC Ripples

This chapter presents the test results in negative DC fields and under negative DC superimposed with AC ripples. More complicated phenomena than in positive DC fields occur with negative DC voltages. A distinguishing tree structure in the superimposed fields is identified and reconstructed in 3D. The role of electron injection and space charge accumulation is further explored, and models are proposed to explain them.

Chapter 6: Summary and Conclusions

This chapter provides a summary of the work presented and conclusions yielded from this project.

Chapter 7: Future Work

This chapter lists some work which can be done in the near future to broaden the insight into this work based on what has been investigated.
Chapter 2  Literature Review

This chapter introduces knowledge from previous research relevant to this project, beginning with voltages to initiate electrical trees, important phenomena prior to initiation and theories on initiation. This is followed by PD measurements and descriptions of tree growth and ends with the research gap where this project can fit into.

2.1  Electrode System for Treeing Tests

2.1.1  Metallic Needles as HV Electrode

The needle-plane geometry shown in Figure 2-1 has been widely used in electrical treeing experiments, where the metallic needle with given taper and tip radius (for example 30° and 3 µm) is connected to the high voltage source to achieve local electric field enhancement while the plane electrode is grounded. The tip radius and the distance between the needle tip and the plane electrode can vary in experiments conducted by different researchers. To ensure electrically sound contact, the bottom surface of the polymer cube is usually coated with a conducting film.

![Figure 2-1 Typical needle-plane electrode system for treeing experiments](image)

When commercial XLPE cables are the test object, the grounding plane can be replaced with either of the semiconducting layers [27] or the cable core [28], as is shown in Figure
2-2. Very rarely, the plane electrode is replaced by a second, grounded needle [29][30], as shown in Figure 2-3 where trees initiated and grew from both needle electrodes, while in the needle-plane geometry trees only initiate and grow from the needle (see Figure 1-6).

![Diagram of needle-plane treeing sample](image1)

Figure 2-2 Needle-plane treeing sample fabricated by commercial XLPE cables.

![Diagram of plane electrode replaced by a second needle](image2)

Figure 2-3 Plane electrode replaced by a second needle, no scale bar available [29]

It is worth mentioning that besides metallic needles, a thin tungsten wire sometimes with a kink along it to generate a divergent electric field was employed to generate the divergent electric field for electrical trees to grow [31]–[33]. In literature below needle-plane geometry was used by default unless noted otherwise.

2.1.2 Work Function of Metallic Needles

High voltage sources can be of various types, and the material of the HV needle electrode has been found to have an impact on electrical tree initiation at AC voltages
and with impulse waveforms [35]. Figure 2-4 shows the correlation between the work function of a needle coating material and tree initiation voltage (defined as 50% probability of tree initiation hereafter) in AC fields [34]: from the data highlighted in the green square of Ag, Ni, Au and Fe, the tree initiation voltage appears to increase as the work function of the metallic needle increases.

Figure 2-4 Tree initiation voltage in AC fields against work function of the metal for needle coating [34]

Aluminium and copper seem to be exceptions in the figure, which might be attributed to the fact that it is easy for oxidation reaction to occur for these metals. The oxidation results in the increase in work function compared with their original values of non-oxidised metals: from 3 eV for aluminium to greater than 6.7 eV for aluminium oxide [36] and from 4 eV for copper to 4.6 eV for Cu₂O and 5.3 eV for CuO [37]. Assuming that Cu₂O is the main product when the oxidation of copper occurs under treeing test circumstances where the concentration of oxygen is believed to be low, then the revised figure is Figure 2-5, which gives more consistency of variation than the original, with Pt being the only exception. It should be also noted that due to the difficulty in machining different metals into the same dimension they were actually evaporated onto identical steel needles to form the electrode [34], and this might partly explain why the tree
initiation voltages were so close to each other, especially for Ni, Au and assumed Cu$_2$O.

![Figure 2-5 Replot of Figure 2-4 with replacement of work functions of Al and Cu with oxidised values.](image)

The effect of metal work function on tree initiation was studied when impulse waveforms with different rise time $t_f$ (wavefront) and different time to half-value $t_t$ (wavetail) were employed to trigger electrical trees in LDPE samples [35]. Impulse descriptions and results are shown below in Figure 2-6 in which the apparent maximum electric field at the needle tip was estimated by Mason’s Equation i.e. (2-1) from [38], which does not take into consideration the effect of space charge (go to Section 2.3 for more information on space charge)

$$E_{max} = \frac{2V}{r \ln (1+4d/r)}$$

(2-1)

where $V$ is the applied voltage, $r$ is the radius of the needle tip, $d$ is the insulation distance between the needle tip and the ground. It is worth mentioning that $E_{max}$ instead of initiation voltage was used for comparison because needles of different materials had different tip radii since it was difficult to machine soft materials such as Al, Ag and Pt to have as sharp a tip as Fe could possibly have.
From the figure it can be seen $E_{\text{max}}$ of tree initiation showed an increasing trend with the increase in work functions of metallic needles when negative impulses, or switching surges as it is called in the figure, were applied; the differences in $E_{\text{max}}$ among the four kinds of needle electrode (roughly 24.5 kV/cm vs. 17.5 kV/cm) were found to be 40% for $t_f=1$ µs and 21.1% (roughly 25.3 kV/cm vs. 20.9 kV/cm) for $t_f=700$ µs. While the relation between the work function and $E_{\text{max}}$ when positive impulses were applied was not as obvious as for negative impulses, there were still differences in $E_{\text{max}}$ among different materials: 4.3% for $t_f=1$ µs and 9.9% for $t_f=700$ µs. Furthermore, $E_{\text{max}}$ was much greater when negative impulses were applied than when positive ones were applied under otherwise identical circumstances, which indicates a polarity difference or polarity effect. In addition, the trend that the difference in $E_{\text{max}}$ was greater under negative polarity than under positive polarity also fitted for oxidised aluminium and original aluminium.

Note: numbers in red next to the materials are the work function from [34], >6.7 in purple is from [36]

*Figure 2-6 Relation between apparent initiation field and rise time of impulses for different needles in LDPE [35]*

The reason why the work function of the metallic needle makes a difference in tree initiation is that work function affects the probability of space charge injection from the needle electrode into polymers. It will be discussed in detail in Section 2.5.1 after the
introduction to space charge (noted as *D1: Effect of metallic work function on tree initiation, Section 2.5.1* hereafter to show that there will be discussion of it in the specified section).

### 2.2 Voltage Waveform and Tree Initiation

Different types of voltage waveforms were employed by researchers in electrical treeing tests and it was found that electrical trees can grow in electric fields of various types: not only in AC fields, DC fields and fields from impulses [35], [38]–[41], but also in superimposed fields by AC plus DC [39][42], AC plus impulses [43] and DC plus impulses [44]. Below is an introduction to tree initiation by different voltage waveforms.

#### 2.2.1 Pure AC Voltages

When describing AC voltages both peak value and rms value were used by different researchers, and they will be all converted to the peak value with one digit after decimal point in the format of ‘X.x kV pk’ for direct comparison. When it is written here as ‘X.x kV (o)’ in text or no indication is given in figures, it means rms or pk was not indicated in the original literature. Needle tip radius (symbol ‘r’ hereafter) and the distance between needle tip and plane electrode (symbol ‘d’ hereafter) will also be listed. The frequency is the utility frequency (50 Hz or 60 Hz based on the country where the researchers were based) unless noted otherwise.

Electrical treeing under AC stresses has been intensively investigated in various materials and Figure 2-7 shows examples of tree initiation in epoxy resin (r = 3 µm, d = 2 mm) at 17.0 kV pk [45], where the initiated trees occurring within one minute had branches and were of less than 50 µm in length. The initiation voltage was found to become lower with the increase in voltage frequency as shown in Figure 2-8 [46] and the initiation time also varied with AC sources: it was usually shorter with higher voltage magnitude and higher frequency [47].
2.2.2 Pure DC Voltages

There are two ways to successfully initiate a tree with pure DC voltages: one is to increase the voltage at a certain ramp rate to a predetermined value and wait for initiation (Procedure 1 or Proc. 1 hereafter), the other is to keep raising the voltage at a certain ramp rate until initiation appears (Procedure 2 or Proc. 2 hereafter). Procedure 2 always results in tree initiation in each test sample while it is not necessarily the case with Procedure 1.

There are far fewer papers about electrical treeing under pure DC stresses because it is very difficult to initiate a tree with pure DC voltage in the first place compared to AC voltage (D2: Much higher tree initiation voltages in DC fields than in AC fields, Section 2.3.2). Pieces of information on tree initiation in pure DC fields were usually given when other research questions were mainly dealt with. One example is the data mentioned
when samples made from epoxy resin (r = 3 µm, d = 2 mm) were tested [45]: it was reported that at pure +60 kV periods of hours or even days were required for tree initiation and initiation was never observed with -60 kV applied to the needle-plane geometry. It is worth mentioning +60 kV was only the voltage at which trees could be initiated rather than being defined as tree initiation voltage. This example falls into Procedure 1 though no ramp rate was given.

Data on LDPE (r = 5 µm, d = 5 mm) showed that tree initiation voltage under pure DC stresses was +40 kV and -45 kV while that with AC applied was only 6.6 kV pk [39]. The initiation voltage in DC fields was determined by Procedure 1: DC voltage was firstly increased by 1 kV/s to a predetermined value and then kept constant for 15 minutes before the sample was taken for examination with a microscope; the voltage at which 50% of the samples developed trees longer than 20 µm was defined tree initiation voltage [39].

A procedure similar to Procedure 1 was employed when tree initiation in silicone rubber (r = 3 µm, d = 3 mm) at different temperatures was investigated [48], where the voltage increased to a predetermined value by 0.5 kV/s and held for 5 minutes before optical observation of initiation. Figure 2-9 shows tree initiation probabilities by different voltages at temperatures ranging from 20 °C to 120 °C: while the voltage with 50% probability of tree initiation under positive stresses was less than +25 kV at various temperatures, the probability under negative voltages up to -35 kV was never larger than 30%. The figure also indicates that a higher temperature resulted in a higher initiation probability regardless of voltage polarities. It is thought to be attributed to polymer property variation caused by changes in morphology of polymer chains and microstructures at higher temperatures. Though no initiation voltage under AC stresses was available in the paper [48], the same research group reported that 6 kV pk was selected as one of the voltages for tree growth observation in silicone rubber at 30 °C with the same geometry [49], indicating 6 kV pk could well initiate trees and probably higher than tree initiation voltage under AC stresses at 30 °C.
Figure 2-9 Tree initiation probabilities in silicone rubber ($r = 3 \mu m, d = 3 \text{ mm}$) by DC voltages at different temperatures [48]

Procedure 2 was employed in [50]: DC was increased by a certain ramp rate till a tree of $\sim 10 \mu m$ in length was observed around the needle tip and the voltage at that very moment was considered initiation voltage. Data on LDPE ($r = 5 \mu m, d = 5 \text{ mm}$) in Figure 2-10 shows that tree initiation voltage, all greater than 40 kV in absolute value, decreased with the rise in the ramp rate for both polarities while it was reported that initiation voltage with AC voltage in LDPE with the same geometry was $\sim 5.5 \text{ kV}$ (o) [51]. Furthermore, the initiation voltage for negative polarity was greater than that for the positive whenever the rising speed was the same for both polarities.

Figure 2-10 Initiation voltage of LDPE ($r = 5 \mu m, d = 5 \text{ mm}$) in DC fields as a function of voltage ramp rate [50]
The difficulty in initiating a tree in LDPE \((r = 3 \, \mu m, d = 10 \, mm)\) with DC voltage also arose at liquid N\(_2\) temperature (77 K), though there was no detail of voltage application procedure: 1) at room temperature tree initiation voltage was +35 kV and -40 kV respectively under pure DC stresses while in AC fields it was 9.9 kV pk; 2) at 77 K the initiation voltage was 59.4 kV pk in AC fields, and greater than 50 kV was recorded for both polarities in DC fields [40]. ‘Greater than 50 kV’ is reasonably assumed that the highest DC voltage applied in [40] was 50 kV and neither +50 kV nor -50 kV had initiated a tree, though no details were available in the paper. Therefore, it could only be correct to say for 77 K that initiation with DC voltage was more difficult than that with AC voltage if it was ‘much’ greater than 50 kV; however, it is well pronounced that at 77 K initiation with DC voltage was more difficult than at room temperature (D3: Higher initiation voltages at 77 K than at room temperature, Section 2.4.5).

Repetitive positive DC cycles ramping up and down at 1 kV/s shown in Figure 2-11 were also employed to initiate a tree but no initiation was seen at up to +70 kV in XLPE \((r = 5 \, \mu m, d = 2mm)\) with no information on negative polarity [41]. At continuous DC voltages no tree initiation was observed at +70 kV for 10.6 hours and at -60 kV for 11.0 hours [41].

![Figure 2-11 Profile of repetitive positive DC voltage cycles without tree initiation](image)

Apart from showing the difficulty in initiating a tree with a DC voltage, the above discussion indicates that the polarity effect which was previously mentioned for impulse fields in Section 2.1.2 also exists in DC fields: \(V_{+dci} = +40 \, kV\) vs. \(V_{-dci} = -45 \, kV\) in [39], \(V_{+dci}\)
= +35 kV vs. \( V_{dc1} = -40 \text{kV} \) in [40], \( |V_{+dc1}| < 25 \text{kV} \) vs. \( |V_{-dc1}| > 35 \text{kV} \) in [48] and \( |V_{+dc1}| < |V_{-dc1}| \) at any DC ramp rate in [50], where symbols \( V_{+dc1} \) and \( V_{-dc1} \) are the initiation voltages with +DC voltage and -DC voltage respectively (D4: Polarity effect, Section 2.3.2).

### 2.2.3 Impulse Waveforms

It is known from Figure 2-6 in Section 2.1.2 that electrical trees could be initiated by impulses and the initiation electric field increased with a longer wavefront duration for both polarities. Other reports, though not many, mentioning tree initiation voltage by the impulse voltage include 1) +38.5 kV and -41.3 kV in LDPE (\( r = 5 \mu \text{m}, d = 5 \text{mm} \)) by a single 1/40 \( \mu \text{s} \) impulse in [39] and 2) +25 kV and -45 kV at 20 °C while +45 kV and -70 kV at 77 K (room temperature) in LDPE (\( r = 3 \mu \text{m}, d = 10 \text{mm} \)) by a single 1/40 \( \mu \text{s} \) impulse in [40]. Ramped impulses with intervals could also be employed to determine the initiation voltage [52]: single 1/40 \( \mu \text{s} \) positive impulse were applied to epoxy resin (\( r = 5 \mu \text{m}, d = 2 \text{mm} \)), starting from 20 kV by 2 kV/step every 10 minutes till tree initiation. The complete data set from [39], [40] and [52] is summarised in Table 2-1, Table 2-2 and Table 2-3.

| Table 2-1 Tree initiation voltage in LDPE with different voltage types [39] |
|-----------------|-----------------|
| Positive Needle | Negative Needle |
| 1/40 \( \mu \text{s} \) impulse | +38.5 kV | -41.3 kV |
| DC (Proc. 1) | +40.0 kV | -45.0 kV |
| AC | 6.6 kV pk |
| Sample | LDPE, \( r = 5 \mu \text{m}, d = 5 \text{mm} \) |

| Table 2-2 Tree initiation voltage \( V_i \) in LDPE with different voltage types at different temperatures [40] |
|-----------------|-----------------|-----------------|
| 293 K (room temp.) | 77 K (liquid \( \text{N}_2 \)) |
| 1/40 \( \mu \text{s} \) impulse (+) | +25 kV | +45 kV |
| 1/40 \( \mu \text{s} \) impulse (-) | -45 kV | -70 kV |
| +DC | +35 kV | \( |V| > 50 \text{kV} \) |
| -DC | -40 kV | \( |V| > 50 \text{kV} \) |
| AC | 9.9 kV pk | 59.4 kV pk |
| Sample | LDPE, \( r = 3 \mu \text{m}, d = 10 \text{mm} \) |
| Note | No description on DC ramp procedure |

| Table 2-3 Tree initiation voltage in epoxy resin under AC and positive impulses [52] |
|-----------------|-----------------|-----------------|
| Ramped 1/40 \( \mu \text{s} \) impulse (+) | Average | Maximum | Minimum | Standard deviation |
| | 31.6 kV | 34.0 kV | 28.0 kV | 2.3 |
| AC | 14.1 kV (o) | 15.0 kV (o) | 12.0 kV (o) | 1.0 |
| Sample | epoxy, \( r = 5 \mu \text{m}, d = 2 \text{mm} \) |
A single 1.2/50 µs standard lightning impulse was employed to initiate a tree in XLPE samples (r = 5 µm, d = 2mm) and 35 kV, at which 5 out of 10 samples initiated, was found to be the initiation voltage [41]. More information is given in Table 2-4. It can be seen that samples would fail before a tree could develop when the voltage was higher than the voltage of 100% probability of initiation (i.e., 50 kV results in insulation failure in 10 out of 10 samples, compared with 45 kV which leads to only initiation in 10 out of 10 samples) For easy comparison, it has been reported by the same authors in [41] (previously mentioned in Section 2.2.2) that no trees were initiated with the same sample geometry at continuous +70 kV DC for 10.6 hours and -60 kV DC for 11.0 hours and repetitive DC at +70 kV.

Table 2-4 Number of tree initiation and breakdown by 1.2/50 µs lightning impulse of different magnitudes [41]

<table>
<thead>
<tr>
<th>Magnitude (kV)</th>
<th>Number of samples</th>
<th>Number of tree initiation</th>
<th>Number of sample failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>6</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>45</td>
<td>10</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2-5 lists tree initiation length where there was initiation in Table 2-4 and the data was rearranged in a box and whisker plot in Figure 2-12 with the mean length marked by a cross. Note that in lightning impulse fields initiation trees were usually a single branch, and the length was determined (shown in Figure 2-13) by the black dashed line rather than the white solid line which was more common in most treeing cases. Compared with tree initiation by AC voltages, initiated trees triggered by the lightning impulse tended to be longer and trees longer than 100 µm occurred at each magnitude. This might indicate different initiation mechanisms by an impulse from those by AC.

Table 2-5 List of tree initiation length by 1.2/50 µs lightning impulses [41]

<table>
<thead>
<tr>
<th>Magnitude (kV)</th>
<th>Tree initiation length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>40, 60, 71, 82, 85, 122, 129, 138, 177, 235</td>
</tr>
<tr>
<td>40</td>
<td>48, 48, 72, 91, 128, 131</td>
</tr>
<tr>
<td>35</td>
<td>33, 40, 41, 55, 102</td>
</tr>
</tbody>
</table>
Chapter 2: Literature Review

From Table 2-1, Table 2-2 and Table 2-3, it is known that tree initiation by impulses was also much more difficult than that by AC voltages, but usually easier than that by pure DC voltages though not necessarily easier for all the samples (D5: Initiation voltage by impulses usually being smaller than that by DC, Section 2.3.2).

2.2.4 DC Superimposed with AC

When DC and AC were superimposed in the format of \( \pm (E_m + E_m \sin \omega t) \) to shift the waveform right above or right below the zero line in coordinate axis, values of \( E_r = 5.0 \) kV rms \( (E_r = 7.1 \text{ kV pk, i.e., } V = +7.1 + 7.1 \sin \omega t \text{ kV}) \) and \( E_r = -4.5 \) kV rms \( (E_r = -6.4 \text{ kV pk, i.e., } V = -6.4 - 6.4 \sin \omega t \text{ kV}) \) were found in the way shown in Figure 2-14 [39] (D6: Results apparently contrary to polarity effect with waveforms by DC plus AC right above or below zero-axis line, Section 2.5.1). Figure 2-15 plots tree initiation voltages when the DC component in absolute value was increased to 10, 15, 20, 25, and 30 kV respectively.
The AC component in tree initiation voltage (the average value determined by dashed vertical lines in Figure 2-15) was found to be in good agreement with $E_+ = 5.0$ kV rms and $E_- = -4.5$ kV rms and very close to pure AC initiation voltage of 4.7 kV rms (6.6 kV pk). Considering that +40 kV and -45 kV is the initiation voltage under pure DC stresses (shown previously in Table 2-1), 30 kV (the maximum DC component magnitude) is 25% smaller than +40 kV and 33.3% smaller than -45 kV, Figure 2-15 also indicates that tree initiation is more a process dominated by AC voltage when AC component reaches a critical value (in this case, $E_+ = 5.0$ kV rms, $E_- = -4.5$ kV rms) but the DC component is relatively low compared to tree initiation voltage with pure DC voltages.

(a) Voltage waveform: $\pm(E_m+Em\sin\omega t)$  
(b) $Em/\sqrt{2}$ (i.e. rms) against tree initiation rate

Figure 2-14 Tree initiation in LDPE ($r = 5 \, \mu m$, $d = 5 \, mm$) with voltages of $\pm(E_m+Em\sin\omega t)$ [39]

Figure 2-15 Extraction of AC component in tree initiation (dashed vertical) in DC and AC superimposed fields [39]
Figure 2-16 plots tree initiation times in LDPE when +20 kV and -20 kV were superimposed onto 10 kV pk AC [42]. -20 kV was reported to reduce initiation time by 1~2 orders of magnitude compared to the case with only 10 kV pk AC while the reduction caused by +20 kV superimposition was mild (D7: Apparently contrary conclusions in DC plus AC fields, Section 2.7.5). It should be mentioned that 10 kV pk AC is higher than 8.4 kV pk AC which would always initiate a tree in LDPE with the same geometry [53] and that 20 kV in absolute value is less than half of the initiation voltage under pure DC stresses in both polarities with the same sample arrangement, which will be detailed in Chapter 4 and Chapter 5.

Figure 2-16 Box and whisker plot of tree initiation time in LDPE (r = 3 µm, d = 2 mm) with DC and AC superimposed voltages, mean values are plotted with a solid circle in red [42]

2.2.5 AC Superimposed with Ramped Impulses

When cables are in operation, there is the likelihood that lightening impulses or switching surges are sometimes superimposed onto the normal operating voltage. Figure 2-17(a) shows the relation between tree initiation voltage and the AC component in fields superimposed by AC and impulses [43]. The voltage application began with 3-minute stress by pure AC which was smaller than the initiation voltage in pure AC fields, then ramped impulses starting from 4 kV were superimposed onto one of the peaks of the existing AC by 4 kV/step every one minute until tree initiation. The superimposed
impulse voltage of tree initiation is shown in Figure 2-17(a); no accurate wavefront and wavetail of the impulse were given, but it was clearly distinguishable from the AC peak, as shown in Figure 2-17(b). It shows that the impulse component required for tree initiation was almost unchanged when the AC component voltage was low but tended to decrease when AC component became higher to reach a certain threshold. Moreover, electrical trees initiated at the moment of impulse superimposition for most cases while exceptions occurred in some samples with higher AC components where trees initiated less than one minute after impulse application (D8: Tree initiation in ramped impulse plus AC fields, Section 2.5.4).

![Figure 2-17 Tree initiation voltage in XLPE (r = 10 µm, d =4 mm) in superimposed fields by AC and impulses [43]](image)
2.2.6 DC Superimposed with Impulses

Superimposed fields with DC and impulses have also been investigated [44][54]. Figure 2-18 shows an example of how DC and impulses were applied to each electrode to form voltage superimposition [44]: the positive impulse was applied to the needle (illustrated as an orange arrow) after 10 minutes of negative DC application to the plane (illustrated as a blue line) to form \( V_{\text{net}} = V_{\text{needle}} - V_{\text{plane}} = (V_i) - (-V_{\text{dc}}) = +V_i + V_{\text{dc}} \) in the figure. \( \pm \) impulses of 1/40, 80/1000, 250/3700 \( \mu \)s and DC = +10, +15, +20, -15, -20, -25 kV increased at 1 kV/sec were used for the superimposition, and the curve representing DC ramp down was formed due to the nature of the circuit and the circuit was short circuited when DC dropped to 5 kV.

![Figure 2-18 Profile of the superimposed voltage at needle (time axis not to scale) [44]](image)

The net initiation voltage \( (V_{\text{net}}) \) plot against DC component \( (V_{\text{dc}}) \) is shown in Figure 2-19. In the figure the DC component is displayed in the form of \( V_{\text{dc}}/V_{\text{dc0}} \) \( (V_{\text{dc0}} \) is the initiation voltage in pure DC fields without impulses, \( +V_{\text{dc0}} = +30 \) kV, \( -V_{\text{dc0}} = -35 \) kV); \( V_{\text{dc}}/V_{\text{dc0}} = 0 \) \( (i.e., \) \( V_{\text{dc}} = 0) \) indicates that there was no DC component existing and therefore was the initiation voltage in pure impulse fields. The net initiation voltage in the 1\(^{st} \) (i.e. illustration in Figure 2-18) and 3\(^{rd} \) quadrants, where the DC and the impulse were of opposite polarities but the same mathematical sign in the \( V_{\text{net}} \) equation \( (i.e., \) \( V_{\text{net}} = +V_i + V_{\text{dc}} \) and \( V_{\text{net}} = -V_i - V_{\text{dc}} \) described as ‘in the same direction’ in the paper), increased along with the increase in the DC component, while otherwise in the 2\(^{nd} \) and 4\(^{th} \) quadrants. In addition, the net initiation voltage went higher when the wavefront of the impulse
became longer in the 1st and 3rd quadrants, whereas it remained almost the same in the 2nd and 4th quadrants (D9: Initiation voltage in Quadrants 1, 3 and Quadrants 2, 4 in superimposition fields of DC and impulse with different wavefronts, Section 2.3.2).

Besides what has been mentioned above, there are other ways to initiate electrical trees in polymers, for instance short-circuit trees (also described as grounding trees or grounded trees by different researchers) and trees from impulses pre-stressed with DC [39][40][44][50]: the former was initiated when both electrodes were short-circuited or the needle electrode was grounded after DC voltage application for a certain time period, in which way much lower DC voltage was required and fairly long tree length has been seen; the latter was initiated by impulses after the removal of pre-stressed DC in opposite polarity and a certain time period of waiting with open-circuit. They were conducted either to further understand the role of space charge in electrical treeing (more information in Section 2.3.3) or merely to facilitate tree initiation before tree growth observation where DC voltage were involved [55].
2.3 Space Charge

Whereas polymeric insulation is widely used in AC and DC power transmission systems, space charge accumulation or the build-up of space charge in DC transmission is a main drawback of increasing the voltage level applied to DC cables. Space charge here refers to the net localised charges present in the bulk of an insulation material. Depending on the scenarios, they can come from electrode injection in laboratory treeing configurations, interfaces such as conductor/semiconductor/insulation that exist in commercial cables, or a conductivity gradient across the insulation itself caused by a temperature gradient in an operating cable [56]–[58]. Below focuses on laboratory treeing samples and therefore electrode injection.

2.3.1 Charge Injection from an Electrode

Charge injection from a needle electrode into polymeric insulation (i.e., laboratory treeing samples) has been experimentally confirmed. The most direct experiment is to measure the change in the sample’s capacitance to calculate the total charge flow to the needle, obtained by 1) a guarded needle to lower the sample’s capacitance to make charge flow by its geometric capacitance comparable with charge flow induced by injected charges and 2) a charge compensating bridge circuit in order to achieve the measurement resolution at the order of magnitude of fC [59]. However, this measurement required a delicately guarded needle and could not provide further information about trapped charges. Three more ways have been reported to confirm the existence of charge injection: 1) free charge release when a sample is short-circuited; 2) trapped charge liberation by laser and 3) thermally stimulated liberation of trapped charges [34]. In Method 1), a high voltage was first applied to a needle electrode to stress a sample for a given time period before being removed to form an open circuit; then the sample was virtually short-circuited by a capacitor with much greater capacitance than the sample; hence the charges which could move freely at the time
would be collected to the capacitor. When the charge formed by the geometrical capacitance of the sample was subtracted from the charge collected, it left the previously injected charges which could move freely when short-circuited. Results by this method with different applied voltages are displayed in Figure 2-20 for 200 µm thick PE film and polyethylene terephthalate (PET) film. The figure shows charge injection occurred in both polarities. In negative polarity the charge injection was mainly electron injection from the negative needle into the polymer while in positive polarity the charge injection was described as hole injection, where electrons in the polymer can move towards the positive needle leading to apparent injection of positive charge carriers. The figure also shows the increase in the applied voltage gave rise to the increase in the charge measured this way in both polarities and that the charge measured under positive voltages was greater than that measured under negative voltages. Moreover, the injection was also polymer dependent with PE exhibiting higher injection level than PET.

Many polymers such as polyethylene comprise of crystalline regions and amorphous regions, forming various defect energy levels or charge traps in the polymer bulk. Charges trapped in deeper trapping sites could remain in polymers when short-circuited
and therefore not measured in Method 1). However, those charges can be excited and released by external energy sources. In Method 2) a laser with a given wavelength was projected to the short-circuited sample and the corresponding current was recorded. In Method 3) a modified TSC (Thermally Stimulated Current) was employed following this procedure: the sample was first stressed at a DC voltage for a given time period at room temperature, rather than at an elevated temperature which is the traditional manner in TSC method, before being short-circuited. In order to increase charge injection level at room temperature, the needle was replaced with a razor; while the temperature was being increased linearly to 85 °C after the short-circuit, and the current was measured with an external circuit. Since it is known from Method 1) that some of the injected charges were able to move freely by short-circuit and be discharged that way, the current thermally released here was considered to be formed by the trapped charges after charge injection from the needle electrode. The measured data with different voltage application times is shown in Figure 2-21 for a PE block (thickness not given). The trapped charge tended to increase with longer time period of voltage application and there were more trapped charge carriers when the razor was applied with the negative voltage than with the positive voltage. It was concluded that the electrons, once injected, are more likely to be trapped in the polymer than holes.

![Figure 2-21 Charge stimulated by TSC method with different DC voltage application time](image)
2.3.2 Role of Space Charge

After knowing of the existence of charge injection, it has been found that there is a ‘critical minimum field’ for charge injection into different polymers. It has been reported that the critical field for electron injection for polyethylene is ~1 MV/cm [60]. This value is much lower than the apparent initiation field under DC voltages in LDPE, which are calculated by Mason equation to be +19.3 MV/cm and -21.7 MV/cm respectively in Table 2-1, and +24.6 MV/cm and -28.1 MV/cm respectively at room temperature in Table 2-2. It is also lower than the apparent initiation field at AC voltages, which are calculated to be 3.18 MV/cm in Table 2-1, and 6.95 MV/cm at room temperature in Table 2-2. It indicates that space charge injection occurs at these voltages and plays a very important role in tree initiation.

The much higher tree initiation voltage in DC fields than in AC fields is attributed to the electric field alleviation by homo space charge injection from the HV electrode into the polymer around the needle tip [38][50]. When a high voltage is applied to the needle tip, charge injection from the metallic needle occurs and leads to a homo space charge accumulation to lower the local electrical field around the tip [50] (Explained D2: Much higher tree initiation voltages in DC fields than in AC fields). The space charge accumulation is considered to increase the effective tip radius and extend the effective length of tip [38], as shown in Figure 2-22, where the tip radius from \( r_0 = 2 \mu m \) to the modified values of \( r = 10 \mu m \) or \( 25 \mu m \) and the tip-plane distance from \( d_0 = 440 \mu m \) to the modified values of \( d = 400 \mu m \) or \( 340 \mu m \) (i.e. the effective needle tip propagates four times further as the modified tip radius) were arbitrarily assumed for the sake of illustration.

The concept of the blunter tip or widened tip together with the corresponding shorter tip-plane distance in Figure 2-22 is thought to explain the local field moderation around the needle tip if the original \((r, d)\) pair in Mason’s equation was replaced with the modified values: modified \((10 \mu m, 400 \mu m)\) and \((25 \mu m, 340 \mu m)\) giving rise to a
maximum field of ~24 MV/cm and ~11 MV/cm compared to (2 µm, 440 µm) resulting in ~88 MV/cm.

Figure 2-22 Probable influence of space charge upon electric field around needle tip [38]

Besides the effect of charge injection on electric field moderation, researchers also discussed the role of trapped charges (after injection) in alleviating the local electric field at the needle tip. Figure 2-23 gives an example of the electric field strength at the needle tip as a function of the density of trapped electrons, which takes space charge (injection and then trapping) and the Poole-Frenkel effect into consideration in a LDPE treeing sample [61]. The plot employs the density of trapped electrons as the independent variable and the model was derived from the Poole-Frenkel effect describing that trapped charges can cause extra current by exciting trapped charges out of traps; however, it did not provide information on the injection phenomenon, and detailed parameters used in the calculation were not available [61]. The figure shows the electric field at the needle tip does not show big differences among different tip radii but is more dependent upon trapped electrons after space charge injection around the needle tip. Taking +40 kV and r = 5 µm, d = 10 mm as an example, while the calculated space charge free apparent electric field is 17.8 MV/cm the corresponding value read from Figure 2-23 is only in the range of ~0.1-0.3 MV/cm, indicating the field is decreased by two orders
of magnitude due to trapped charge carriers resulted from charge injection from the metallic electrode. It should be noted that the plot in the figure only applies in polyethylene with the specific sample configuration illustrated in the figure and different material and geometries lead to different densities of trapped charge carriers even at the same voltage.

![Diagram showing electric field at the needle tip against the density of trapped electrons in LDPE][61]

Figure 2.23 Electric field at the needle tip against the density of trapped electrons in LDPE [61]

The electric field alleviation by charge injection not only explains why much higher voltages are required to initiate a tree in both DC and impulse fields but is also responsible for the polarity effect mentioned in Section 2.2 when it is found that in both µs impulse and DC fields the tree initiation voltage is higher when negative voltage is applied than when positive voltage is applied. This is because at a metal-polymer interface the potential barrier for electron injection is usually lower than that for hole injection [62], which gives rise to more charge carrier injection and therefore more significant mitigation effect on the local electric field at the needle tip when it is stressed with negative voltages. Hence the tree initiation voltage by DC voltages or impulses is higher in the negative case than in the positive case, as is shown in Table 2-1 and Table 2-2 (Explained D4: Polarity effect).
It is worth mentioning that there is no polarity effect for nanosecond impulses of which the impulse duration was considered to be shorter than the time constant of space charge injection [39]. In impulse cases in Section 2.2.3, it can be assumed (the authors view) that space charges do not have sufficient time to respond during the 1 µs or 1.2 µs wavefront to build up a sufficient space charge accumulation to alleviate local electric field as much as the DC could do in the otherwise identical cases [39]. This results in the initiation voltage by impulses usually being smaller than that by DC (Explained D5: Initiation voltage by impulses usually being smaller than that by DC).

Space charge is widely accepted to be responsible for many phenomena and employed in explanations, especially when DC is involved. For example, in the case of Figure 2-19, where the net initiation voltage $V_{net}$ in the superimposition of DC and impulse voltages was found to increase with DC component in Quadrants 1 and 3 while decrease in Quadrants 2 and 4, it was explained to be due to 1) the effectively magnified tip radius in Quadrants 1 and 3 (impulse and DC in the same direction) by space charge accumulation to relieve the local field, resulting in a higher apparent initiation voltage, and 2) local field increase between the needle tip and the space charge accumulation around the tip in Quadrants 2 and 4 (impulse and DC in the opposite direction) [44]. This is thought to be a sensible explanation. That impulse wavefronts made little difference in Quadrant 2 and 4 but $V_{net}$ increased with wavefronts in Quadrant 1 and 3 was also attributed to space charge, although the description given in the paper is unclear [54]. However, what might be responsible for this is thought to be as follows. In Quadrant 2 and 4 the local field increase by polarity reversal from DC to impulse plays a pronounced role compared with space charge accumulation by impulse. While in Quadrant 1 and 3 space charge injection by impulse is of the same polarity as that by existing DC and therefore longer wavefronts provide sufficient time for space charge of the same polarity to alleviate local field, resulting in a higher initiation voltage (Explained D9: Initiation voltage in Quadrants 1, 3 and Quadrants 2, 4 in superimposition fields of DC and impulse with different wavefronts).
2.3.3 Short-circuit Tree Length

After acknowledging the existence of both charge injection and short-circuit trees (especially when one of the ways to confirm the existence of charge injection is by virtual short-circuit, Figure 2-20, Section 2.3.1), it can be assumed that they are closely related. Therefore, the length of short-circuit trees was measured to provide an idea of how far injected charge carriers could travel or penetrate the polymer [50]. Figure 2-24 shows the tree length in polyethylene at 30°C plotted against 15 minutes of DC stress in both polarities before short-circuiting the electrode pair: the DC ramp rate was 0.2 kV/sec, and the rise time of the DC was included in the 15 minutes of voltage stress. The tree length was seen to increase with DC voltage magnitude in both polarities and the tree length after negative DC stresses was an order of magnitude longer than that after positive DC stresses when the voltage in absolute value was greater than or equal to 40 kV (100-200 µm compared to 10-20 µm), indicating injected electrons had higher mobility and travelled further than injected holes.

![Figure 2-24 Effect of DC voltage on short-circuit tree length in polyethylene at 30 °C, no (r, d) information [50]](image)

2.3.4 Space Charge Transfer in AC Fields

Considering 1 µs duration is sufficiently long to result in space charge build-up (though not as considerably as in DC cases [39]), in AC fields of utility frequency with a full cycle
time of 16.6 ms (60 Hz) or 20 ms (50 Hz), space charge is also thought to play a key role [63]. A charge bias model was put forward by Tanaka to describe space charge transfer between metallic needle and polymer base in AC fields, as shown in Figure 2-25, based on the information that more electrons than holes are injected into the polymer and that electrons are more likely to be trapped than holes. It describes the process in terms of electrons; but holes behave in a similar way. A homo space charge area forms when electrons are injected from the needle to the polymer in the negative half cycle, as shown in Figure 2-25(a). The electron injection is believed to take place via Schottky emission or field emission from the metallic needle when the voltage reaches the corresponding threshold [24]. Some of the injected electrons are trapped and will remain in the polymer even when the AC waveform moves to the consecutive positive half cycle, as shown in Figure 2-25(b), which results in a negatively biased area around the needle tip in the positive half cycle. For the positive charge carriers, the trapped electrons form a hetero space charge area which would increase the local electric field in the positive half cycles. The distance of 20 µm is derived from the initial tree length (6 to 18 µm) from experimental data to show the spread of electron injection. Charge injection and extraction repeats in consecutive AC half cycles.

![Figure 2-25](image.png)

**Figure 2-25** Injected and remaining electrons in AC half cycles [63]

### 2.4 Phenomena prior to Tree Initiation

When voltages are applied to the needle electrode in the treeing sample, it takes some time (initiation time) before a tree is observed visually and this is sometimes called
incubation stage [34]. Physical and chemical changes have been found to feature during this stage.

2.4.1 Electroluminescence (EL)

Broadly speaking, electroluminescence (EL) is a phenomenon occurring when electrical energy is transformed into light emission; here it refers to the optical emission associated with charge injection into electrically stressed dielectrics when the electric field reaches a critical minimum value or a threshold value. In fact, in electrical treeing tests the onset fields for EL and charge injection were reported to be in the same range [60] and that the onset of EL coincided with space charge injection [24]. Figure 2-26 shows an EL photograph in polyethylene obtained at liquid nitrogen temperature (77 K) under AC fields [60].

The light emission in the photo was confirmed by spectral analysis to be the EL, rather than caused by partial discharges (PDs) within cavities or voids. A broad spectrum in both the visible range and near-ultraviolet range was detected in EL, while the light emitted from PDs has peaks in UV ranges [60][64]. A sophisticated EL technique was reported to have sufficient sensitivity to reveal the faint light of EL [65] and succeed in detecting EL as a sign of degradation prior to tree initiation in 500 kV XLPE cable [66].

No EL was detected in needle-plane polyethylene samples at DC voltages and rectified AC voltages in [67], as shown in Table 2-6.
Table 2-6 Different voltages applied to polyethylene samples and EL behaviour [67]

<table>
<thead>
<tr>
<th>Voltage waveform</th>
<th>Maximum value of voltage</th>
<th>Maximum apparent electric field by Mason Equation (MV/mm)</th>
<th>EL threshold field (MV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Hz AC</td>
<td>30 kV</td>
<td>2.1</td>
<td>~ 1.0</td>
</tr>
<tr>
<td>Positive DC</td>
<td>50 kV</td>
<td>3.5</td>
<td>EL not observed</td>
</tr>
<tr>
<td>Negative DC</td>
<td>50 kV</td>
<td>3.5</td>
<td>EL not observed</td>
</tr>
<tr>
<td>Positive rectified AC (50 Hz)</td>
<td>45 kV</td>
<td>3.15</td>
<td>EL not observed</td>
</tr>
<tr>
<td>Negative rectified AC (50 Hz)</td>
<td>45 kV</td>
<td>3.15</td>
<td>EL not observed</td>
</tr>
</tbody>
</table>

However, the results do not necessarily mean there is no EL under DC fields or rectified AC fields, it still makes sense if the threshold for EL occurrence under either field is higher than was employed in the paper, considering that tree initiation voltage under either field is higher much than that under AC fields [68]. In fact, EL was reported to occur under DC fields and fields by impulses with different sample arrangements and uniform electric field distribution other than the needle-plane geometry with a highly divergent field [69]–[71].

Though there are different explanations for EL formation, it is commonly accepted that it is associated with charge injection. Here are two proposed mechanisms [60][72][73]:

1) polymer molecule excitation or ionisation attributed to hot electron collision

When voltages are applied to the needle, injected electrons are accelerated by the electric field and gain sufficient kinetic energy to become hot electrons. They collide with and transfer energy to the polymer molecules which in turn can be excited or ionised. Excitation occurs when the electrons in polymer molecules gain energy higher than the ground state and ionisation occurs when the electrons in polymer molecules are promoted to the conduction band; the latter requires higher level of energy than the former. Light is emitted either when excited chromophores return to the ground state after excitation or when charges involving luminescent centres recombine after
ionisation. Therefore, the kinetic energy acquired by hot electrons through the electric field plays a key role in polymer molecule excitation.

2) recombination between charge carriers of opposite polarities

This explanation holds that bipolar charge injection is the essential element for electroluminescence. During the negative half cycle of AC voltage, electrons are injected into the polymer and some of them are captured by trapping sites. When the voltage goes into the positive half cycle, holes are injected and most electrons in shallow traps are extracted and move back to the needle electrode, while the ones in deep traps stay in the polymer and recombine with the injected holes. Light emits when the recombination occurs. Though there is no field threshold for charge recombination [74], there is one for charge injection. Hence, there is a field threshold for EL occurrence in both explanations.

Considering charge injection and extraction is widely accepted to have caused EL, the diameter of the illuminated area in Figure 2-26 (~20-30 µm) might be considered as an indicator of charge injection distance in AC fields.

### 2.4.2 Free Radicals

As is mentioned above, electrons can be accelerated and therefore gain kinetic energy in an electric field during injection. When injected electrons obtain energies of the order of molecular bond energies within polymers, they become capable of breaking bonds. C-C bonds with an average bond energy of 3.60 eV and C-H bonds of 4.28 eV [75] are the most common bonds in polymers, especially in polyethylene. It has also been confirmed that when electrons with a kinetic energy of 3-4 eV are sufficient to break bonds in polymers [76]. When the accelerated electrons collide with polymer molecules and break bonds, free radicals are produced. Free radicals feature unpaired electrons which can be detected by ESR (electron spin resonance). Figure 2-27(a) shows the
amount of free radical produced around a needle tip in a LDPE sample against the applied AC voltage up to 8 kV (o) [77]. There was no free radical detected below 4 kV (o) and a considerable increase was observed above 5 kV (o), which was also determined as the onset voltage of electroluminescence for the sample. Considering that tree initiation voltage for the sample is calculated to be higher than 12.4 kV (o) based on the highlighted squared point (>350 kV/mm) in Figure 2-27(b), free radicals begin to form well below the tree initiation voltage.

![Diagram](image)

*Figure 2-27 Relation between the amount of free radical (measured by ESR) and applied voltage [77]*

### 2.4.3 Deteriorated Region

A deteriorated region has been found to form when a dielectric is stressed for a long time under an electric field higher that the threshold field for charge injection. Figure 2-28 shows the deteriorated region dyed with methylene blue in LDPE at 77K [78]. Methylene blue is a chemical indicator of oxygen-rich environments [79], which might suggest bond break, and the subsequent reaction between the free radical and the oxygen which can exist in the free volume of the polymer. The dyed region was found to be very similar to the EL region in terms of shape, dimensions, and position, though it was a little smaller than the EL region, as shown in Figure 2-29 plotting dimensions of...
the two regions against applied voltage. It is worth mentioning that the diameter of both regions is in the range of ~5-15 µm, which is in the same range of tree initiation length under AC stresses.

![Image](2-28 Deteriorated region dyed with methylene blue: 42.4 kV pk for 3 hrs in LDPE at 77 K [78])

![Image](2-29 Diameter of deteriorated region and luminescent region of EL vs. applied voltage [78])

Chemical analysis of the deteriorated region in polyethylene prior to tree initiation was reported with the results summarised below [80]:

1) The absorption peaks at 1730, 1640 and 1540 cm\(^{-1}\) were observed in FT-IR (Fourier-transform infrared spectroscopy) differential spectrum, which generally results from the stretching vibration of carbonyl groups (C=O);

2) A peak of 1650 cm\(^{-1}\) appears in the Raman difference spectrum, which is attributed to the stretching vibration of double bond (C=C). The existence of C=O and C=C is thought to strongly suggest the occurrence of free radical and chain scission.

3) The Raman difference spectrum has peaks at 2900, 1440 and 1290 cm\(^{-1}\), which are due to the structure of polyethylene (-CH\(_2\) stretching vibration), however, the width of the peaks was broader than normal, suggesting that amorphous content increases in the deteriorated region.
A TEM (transmission electron microscopy) image of the deteriorated region in polyethylene is given in Figure 2-30 [81]. Compared with the normal region consisting of lamellae (their structure is relatively orderly) in Figure 2-30, the destruction of the lamellar structure and an increase in amorphous content result in more electron scattering (therefore less electron transmission) and correspond to dark areas in a TEM image [82], which is indicated as deteriorated region. The destruction of lamellae is in accord with the larger peak widths in Raman spectrum in [80].

![Figure 2-30 TEM image of deteriorated region in polyethylene](image1)

SEM (scanning electron microscopy) observation reveals small voids with diameters less than 0.5 µm existing in the deteriorated region, as shown in Figure 2-31, while it is confirmed before testing that no voids exist around the needle tip [81]. The structure with micro voids is also referred to as low-density domain or region and considered to provide a longer path for electron acceleration [62], which will in turn facilitate the impact excitation and ionisation by hot electrons mentioned in Section 2.4.1.

![Figure 2-31 SEM photo of deteriorated region in polyethylene](image2)
2.4.4 Localisation of Chemical Bonds

While the chemical analysis discussed above focused on a region as a whole around the needle tip prior to tree initiation, locating the exact spots of specific chemical bonds has been made possible with the application of AFM-IR to epoxy treeing samples at incubation stage [83]. AFM-IR (atomic force microscope-infrared spectroscopy) is a combination, as the name suggests, of scanning probe microscopy to provide spatial information and infrared-spectroscopy to tell chemical bonds. Figure 2-32 shows the schematic diagram of AFM-IR with top-down illumination used in treeing samples: one spot of the sample surface is illuminated by a pulsed laser with a certain wavelength while an AFM probe is scanning across it; if the excitation energy of a molecule at the spot equals to the laser’s energy, the AFM probe and therefore the cantilever will vibrate with the excited molecule; then the vibration of the cantilever leads to deflection change and is recorded by the photodetector; the whole surface will be scanned and the laser source is tuneable and includes IR spectrum [84].

![Figure 2-32 Schematic diagram of AFM-IR with top-down illumination](image)

Figure 2-33 shows the AFM-IR absorption maps of a 30 µm x 30 µm square from an epoxy sample stressed at 11.3 kV pk for 40 minutes without tree initiation: the dark triangle area in the optical image in a) is the location where the needle electrode used to be before it was taken out for sample polishing to exposure a high quality surface. Figure 2-34 groups the maps based on the degradation locations [83]. Case 1 indicates areas immediately in front of the needle with the absorption of 1656 cm\(^{-1}\), 1702 cm\(^{-1}\),
1726 cm\(^{-1}\) and 1742 cm\(^{-1}\) which can be assigned to C=O bond and C=C bond. It is in agreement with the findings in [80], but this time it was more accurately located. Case 2 includes the absorption of 1056 cm\(^{-1}\), 1132 cm\(^{-1}\), 1248 cm\(^{-1}\) and 1288 cm\(^{-1}\) which was considered most probably assigned to an ether bond though no reason for its formation was given. Case 3 refers specifically to the absorption of 1448 cm\(^{-1}\) which was assigned to CH\(_3\) bond. The overlap of areas in the Case 3 and Case 1 and the fact that CH\(_3\) bond has been detected in multiple samples [85] prior to tree initiation may indicate CH\(_3\) bond is a precursor to C=O bond.

**Figure 2-33** AFM-IR absorption maps: a) optical image, b) 1056 cm\(^{-1}\), c) 1132 cm\(^{-1}\), d) 1248 cm\(^{-1}\), e) 1288 cm\(^{-1}\), f) 1360 cm\(^{-1}\), g) 1448 cm\(^{-1}\), h) 1604 cm\(^{-1}\), i) 1656 cm\(^{-1}\), j) 1702 cm\(^{-1}\), k) 1726 cm\(^{-1}\), l) 1742 cm\(^{-1}\). Colormap: red indicating higher absorption and green lower. [83]

**Figure 2-34** Illustration of degradation groups based on chemical bond locations. [83]
2.4.5 Role of Oxygen

From the chemical analysis mentioned above, autoxidation shown in Figure 2-35 has been suggested to exist and play a key role in tree initiation [60]: when hydrogen (·H) leaves the end of a chain, the free radical forms; when it reacts with oxygen which might naturally exist in the free volume of the polymer, hydroperoxide (ROO·) is produced; hydroperoxide is unstable and can break more bonds, especially the hydrogen at the end of a chain, and reproduces more free radicals. The activation energy of autoxidation is low and repeats itself; as a result, chain scission occurs.

![Autoxidation process diagram](image)

Given the autoxidation process in the figure above, where there is less amount of oxygen or less amount of autoxidation reaction, higher initiation voltage under AC stresses should be expected, which is the case in degassed samples (S1 for short), degassed samples also impregnated in N₂ before test (S2 for short) and samples with antioxidant additives (S3 for short) [86]–[89]. The removal of oxygen from the free volume in S1 and S2 reduced the amount of oxygen itself and antioxidant additives suppressed autoxidation even though there was a ‘normal’ amount of oxygen in free volume in S3, which as a result led to higher initiation voltages. Higher initiation voltage was also seen in treeing at 77 K where less motion between rigid and ‘frozen’ oxygen and polymer...
molecules and higher probability of the recombination of free radicals at 77 K were considered to hinder autoxidation resulting in a higher tree initiation voltage [40] (Explained D3: Higher initiation voltages at 77 K than at room temperature).

2.5 Theories on Tree Initiation

Based on the discussion in Section 2.4, it is widely accepted that breaking of bonds and chain scission is the direct cause of tree initiation in polymers. However, opinions differ when it comes to the cause of bond break and the consequent chain scission. Here some key theories are summarised. It is worth mentioning that these theories focused on tree initiation under AC stresses, as most of the research was conducted under AC stresses.

2.5.1 Charge Injection & Extraction

This theory is based on charge injection and the acceleration of charge carriers in polymer free volume under AC fields. During the repetition of each cycle, some of the charge carriers can gain sufficient energy to break bonds and degrade polymer molecules into lower molecular weight products and gases, leading to the formation of micro voids and hollow channels; when the channel becomes large enough to maintain gaseous discharges, it can be considered that an electrical tree has initiated and will grow further driven by gaseous discharges [34][63].

This theory successfully explains the relation between tree initiation voltage and work function of the needle electrode mention in Section 2.1.2. The work function governs how much energy an electron needs to escape outside the solid surface and therefore the electron injection probability from the metallic needle into the polymer: the higher the work function of the metal, the higher the potential barrier electrons need to overcome, the more difficult for electrons to be injected into the polymer, the higher the tree initiation voltage would be (Explained D1: Effect of metallic work function on tree initiation).
In the case of Figure 2-14 \(E_+ = +7.1 + 7.1\sin\omega t\) kV and \(E_- = -6.4 - 6.4\sin\omega t\) kV were found to be the tree initiation voltage which seemed contrary to the polarity effect, tree initiation is thought to be a combined result of both electric field moderation effect by space charge accumulation and injected charge acceleration by the external electric field. In this case the DC component is very low compared to the pure DC initiation voltage, therefore field moderation effect is thought to be less significant, while space charge acceleration plays a dominant role. When the waveform is all below the zero axis, injected charges are mainly electrons, the accelerated electrons collide with molecules and lead to tree initiation over time whereas holes usually have less mobility. That is why the absolute value of \(|E_-| = 6.4\) kV is lower than \(E_+ = 7.1\) kV. Furthermore, it indicates from Figure 2-15 that a DC component higher than 30 kV might be required to make electric field moderation, which results from space charge accumulation, dominate tree initiation rather than electron collision with molecules (Explained D6: Results apparently contrary to polarity effect with waveforms by DC plus AC right above or below zero-axis line).

2.5.2 Photodegradation by EL

It has been shown in Section 2.4 that EL can occur at an AC field much lower than the apparent electric field of tree initiation and that EL includes light in the visible range and the near-ultraviolet range. On the other hand, samples with EL detected were reported to have always developed trees and ultraviolet absorbers and light stabilisers were found to either increase tree initiation voltges or prolong tree initiation time [64][89]. It have been suggested that the UV radiation in EL leads to photodegradation of the polymer which in turn causes bond break, free radical formation, chain scission and the sequent microvoids and tree initiation. This thoery can explain why the EL onset voltage coincided with the votage when free radicals began to increase in Figure 2-27 in Section 2.4.2.
2.5.3 Maxwell Electromechanical Stress

This theory was first put forward in the early research on tree initiation in polymers, which suggested that tree initiation resulted from molecular deformation caused by Maxwell electromechanical stress around the needle tip induced by the high voltage field [90]–[92]. When an AC electric field is applied to the needle electrode, a repeated Maxwell stress, the value of which is $\frac{1}{2} \cdot \varepsilon_r \cdot E^2$ (where $\varepsilon_r$ is the permittivity of the dielectric), applied a compression force perpendicular to electric field to the polymer. When the stress exceeds a critical value, molecular deformation occurs and results in crazes or cracks. With the continuous voltage application over time cracks develop into micro voids in which partial discharges lead to local breakdown, which in turn enlarged and expand the voids to accommodate further partial discharges until an optical tree could be observed [90]. However, this theory cannot explain phenomena such as polarity effect the relation between initiation voltage and the work function of the needle electrode.

2.5.4 Local Intrinsic Breakdown

The above theories all describe a process of damage accumulation which begins to occur at voltages well below tree initiation voltages. However, a local intrinsic breakdown which usually occurs at a short time period can also be a reason for tree initiation if the local electric field around the needle tip is sufficiently high, which can be caused by, for example, the hetero space charge accumulation (trapped electrons in previous negative AC half cycle) in a positive AC half cycle [24] or the ‘inverse’ of field in short-circuit trees at the instant of short-circuit [50]. Tree initiation by impulse after prestress of DC of the opposite polarity in [50] might be also a result of local intrinsic breakdown induced by polarity reverse, as well as the sudden electric field build-up in the cases by pure impulse presented in Section 2.2.3.
It is worth mentioning that tree initiation is believed to be a dynamic process considering that many parameters such as electric field distribution and space charge build-up are time dependant. Furthermore, damage in polymers by external fields accumulates over time and therefore even polymer properties are time dependant. One cannot tell for sure which mechanisms above are directly responsible at the very moment when first tree channels appear. For example, photodegradation and electron collision can occur simultaneously, and local intrinsic breakdown can even happen in AC fields.

In the case of Figure 2-17 (ramped impulses superimposed onto one peak of AC voltage) local intrinsic breakdown by impulses is thought to be the dominant mechanism for tree initiation when the AC component is relatively low, which explains why the impulse required for tree initiation was almost unchanged when the AC component voltage was low. Initiation being a local intrinsic breakdown also explains why tree initiation in most cases occurred at the very moment of impulse superimposition onto the existing AC, i.e., in a very short time period. When the AC component increased in magnitude to reach a certain threshold, it could accumulate considerable damage before initiation and the previous impulses at a lower magnitude also built up damage, which eventually led to lower impulse magnitude when initiation occurred. The exceptions of time delay in initiation with higher AC voltages might also be a proof of initiation being an accumulation process (Explained D8: Tree initiation in ramped impulse plus AC fields).

2.6 Partial Discharge (PD)

Partial discharge (PD) is localised electrical discharge occurring inside an insulation system or on the surface of it. PD does not lead to immediate failure of the insulation but only partially bridges the insulation [93]. PD signals have been considered a key factor in tree growth [94]–[96]. This section will focus on PD measurement to facilitate the following discussion of tree growth in Section 2.7 and the experimental arrangement in Chapter 3.
2.6.1 PD Measurement

PD represents itself in many ways, such as emission of light, heat and sound, current pulses and by-products caused by chemical reactions, hence PD measurement is possible by collecting signals from one or more of these phenomena. The following model explains the detection of current pulses. Here the focus is on the internal discharges inside solid insulation since those PD signals apply in the conditions where electrical trees are growing.

Illustrated in Figure 2-36 is the most commonly employed model when dealing with partial discharges under AC stresses [97]. It describes a void enclosed in a dielectric using three capacitors: \( C_d \) is the bulk capacitance of the dielectric; \( C_s \) represents the part of the dielectric in series with the void and \( C_g \) is the capacitance of the void.

![Diagram of capacitive model for partial discharge analysis in solid insulation](97)

It can be seen from the figure above that \( C_g \) and \( C_s \) forms a voltage divider where the voltage drop across the void \( U_g(t) \) is lower than that across the bulk dielectric \( U_d(t) \). When the dielectric is electrically stressed, there is corresponding voltage drop \( U_g(t) \) across the internal void. When the electric field induced by \( U_g(t) \) becomes higher than
the dielectric strength of the gas inside the void $U_Z$, a total breakdown of the gas will occur inside the void, which is simulated by the switch $S$ closing, resulting in the current pulse $i_g(t)$ and $U_g(t)$ beginning to drop in Figure 2-36. As $U_g$ drops to $U_r$ (termed as residual voltage which can be a value close to zero or smaller than $U_Z$ [98][99]), the discharge cannot be sustained and will be extinguished. With an AC stress across the dielectric, the process repeats itself when the electric field induced by $U_g(t)$ again becomes higher than the dielectric strength of the gas inside the void $U_Z$. The repeated occurrences of current pulses under AC stresses are shown in Figure 2-37, where the apparent discharge magnitude is calculated by integrating the current pulse over its duration.

![Figure 2-37 Current pulses when PD occurs and apparent discharge calculation](image)

Two methods of current pulse acquisition compatible with IEC 60270 or its equivalent BS EN 60270 [93] are shown below: one using a coupling device together with a coupling capacitor and the other using high-frequency current transformer (HFCT).

1) Coupling Device and Coupling Capacitor

Based on the desired sensitivity, there are two types of setup to record the current pulses using a coupling device together with a coupling capacitor, as shown in Figure 2-38 and Figure 2-39. There are four components in the figure: 1) a blocking impedance
Z which blocks rapid recharging from the power supply to ensure that the current flows within a closed loop where the signals are to be recorded, 2) a coupling capacitor $C_k$ to guarantee the recharging process of the test object $C_a$ when PD occurs, 3) a coupling device CD which captures the current signals and separates the high-frequency pulses from the low-frequency ones, and 4) a measuring instrument MI which converts the input current signals into the output voltage signals and calculates the apparent charge of PD signals.

![Diagram 1](image1)

**Figure 2-38 PD measurement with coupling device CD in parallel with the test object $C_a$ [93]**

![Diagram 2](image2)

**Figure 2-39 PD measurement with coupling device CD in series with the test object $C_a$ [93]**

The one which is most commonly employed is shown in Figure 2-38, where the coupling device CD is connected in series with the coupling capacitor $C_k$ while in parallel with the test object $C_a$. The measuring device will not be affected when a total breakdown occurs in the test object, which is a huge advantage in terms of safety of employing the setup. According to IEC 60270, a good sensitivity can be achieved when $C_k/C_a \approx 10$. The other setup shown in Figure 2-39 connects the coupling device CD in series with the test object $C_a$, in which case, the test object $C_a$ is recharged from both stray capacitances and the
coupling capacitor $C_k$ after every partial breakdown. Therefore, this setup resulting in stray capacitances to reload the sample can be used when a higher sensitivity is required. However, its disadvantage is that when a total breakdown of the test object occurs, either inside the object or on its surface, the coupling device CD would be exposed to the full test voltage. In this case it is likely that the coupling device CD and the measuring instrument MI will be damaged even though there are built-in protection circuits in CD and MI.

2) High-frequency Current Transformer (HFCT)

HFCTs are widely used for PD detection in HV cables because it can be installed by encircling the ground cable connection which is located at a safe distance from HV area, as is shown in Figure 2-40 [101]. The core of a HFCT is an induction coil of which the output is the induced voltage proportional to the change rate of the input current, from which the current pulses can be calculated.

![Figure 2-40 HFCT encircling the cable grounding for PD measurement [101]](image)

The measurement sensitivity is usually not comparable between different sensors which measure different signals: $C_k$ measures the PD current pulse itself while HFCT measures the induced signal by the PD current flowing through the cable connection it encircles. The choice of sensors (coupling capacitor $C_k$ or HFCT) is usually based on physical scenarios. For example, when a cable joint is the test object, HFCT is usually the only feasible way to conduct PD measurement, as shown in Figure 2-41, where HFCTs encircle the connecting cables between joints or terminals.
2.6.2 Tree Initiation and Detectable PD

Apart from being an indicator of tree growth which will be elaborated in the next section, PD signals can also be used to help identify tree initiation when 1) PD measurement has sufficiently high sensitivity and 2) it can be confirmed that there are no microscopic air gaps around the needle tip (detailed information in Section 3.2), for example with PD noise below 1 pC (0.35 pC) and Micro-XCT confirmation of no air gaps [53]. 10-55 µm air gaps which formed naturally in the front of the needle tip, which are usually not visible in conventional optical images, provide sufficient path for electrons to accelerate in and therefore lead to PD signals (if the sensitivity can be sufficiently high) before tree initiation while samples without air gaps show no PD signals prior to initiation.

2.6.3 PD Analysis Methods

A PD measurement unit usually provides 1) the magnitude of each PD event or pulse, 2) the time and 3) the phase degree when an individual PD event occurs. With this information, PD signals can be presented statistically and further analysed.

Though the following sections in this chapter, as well as Chapter 4 and Chapter 5, will provide specific examples of PD analysis methods in the context of tree growth, here is a summary of the commonly employed ones. PRPD (phase-resolved partial discharge) is the most common plot in PD analysis. This plot describes the distribution of PD events over phase and the PD density coded by colourmap. The shape variations of the PRPD
patterns indicate tree growth stages [42]. PSA (pulse sequence analysis) plots the voltage difference (or the PD magnitude difference) between two consecutive PD events against their time difference (or their phase difference). Unlike PRPD patterns which merely plot PD events statistically, PSA requires at least two PD events occurring in one cycle, otherwise there is no pulse sequence to analyse [103]. PD phase histogram is another way to observe in detail the phase distribution of PD events. PD magnitude trend (or the PD maximum magnitude variation) over test duration indicates how the PD magnitude evolves. PD occurrence per cycle (or per second if there is no phase information in PD measurement) is also useful to monitor PD variation. It should be noted that PD signals can be presented in many ways. Each plot mentioned above has its own emphasis and various plots combined together give a more comprehensive understanding of treeing.

2.7 Electrical Tree Growth

Once channels begin to form in the initiation stage, trees grow at different rates into different shapes at different voltages, with PD activities and chemical reactions along tree channels. This section includes how to describe various tree types, the properties of tree channels and tree growth where various voltages are involved.

2.7.1 Fractal Dimension

The concept of self-similarity and fractal geometry was first introduced to analyse various shapes in nature [104]. Electrical tree structures have been shown to exhibit the fractal property and therefore fractal dimension \( D_f \) has been used as a tool for describing tree structures [105][106]. The most common method to calculate \( D_f \) is box counting, as shown in Figure 2-42: covering the tree structure with square boxes and if the relation

\[
N(r) \propto r^{-D_f}
\]

(2-2)
applies (in fact, structures with the fractal property always apply as shown in the log-log plot in Figure 2-43), where \( N(r) \) is the number of square boxes and \( r \) is the side length of boxes in pixel, the absolute value of the line slope in the figure (number 1.47) is the fractal dimension.

\[ D_f \]

Figure 2-42 Box counting to calculate \( D_f \): (a) 2D photo of tree, (b) digitalised tree photo, (c) tree structure covered by square boxes of 30 x 30 pixels, (d) tree structure covered by square boxes of 10 x 10 pixels [106]

Figure 2-43 Log-log plot of \( N(r) \) and \( r \) in structures with fractal property [106]

The \( D_f \) of bush trees based on 2D photos was shown to be higher than that of branch trees, with the former being higher than 1.8 and the latter lower than 1.5 [107]. While 2D imaging has been the main tool of tree growth observation for many years, 3D imaging or volume rendering techniques, for example XCT (see Section 3.3 for more detail) and SBFSEM (Serial Block-Face Scanning Electron Microscopy), have also been
employed to provide more details of tree structures [108][109]. Where 3D volume rendering is available there are three 2D $D_f$ in the three orthogonal planes ($xy$, $yz$ and $xz$) and the 3D $D_f$ ($3dD_f$) can be calculated by replacing the box pixel with the cube voxel. Considering that the three 2D $D_f$ are very close [108], they are represented by an average 2D $D_f$ ($2dD_f$-Average) hereafter. Figure 2-44 shows 3D volume rendering of various trees in epoxy resins and Table 2-7 lists the corresponding $2dD_f$-Average and $3dD_f$ for each sample in the figure. While an obvious difference can be spotted between S3 and S5 with the other samples, the average 2D $D_f$ fails to reflect this because too many branches overlap in 2D projections. The structure in S3 and S5 is called a dense bush tree and it can only be accurately described by $3dD_f$ which is larger than 2. It has also been found that the mean diameter of branch tree channels is 2 µm and that of bush tree channels is 3-4 µm [109].

![Figure 2-44 3D volume rendering of various trees in epoxy [109]](image)

Table 2-7 Average 2D fractal dimension vs. 3D fractal dimension of tree structures in Figure 2-44 [109]

<table>
<thead>
<tr>
<th>Sample</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2dD_f$-Average</td>
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<td>1.75</td>
<td>1.76</td>
<td>1.66</td>
<td>1.79</td>
<td>1.69</td>
<td>1.69</td>
<td>1.69</td>
<td>1.76</td>
</tr>
<tr>
<td>$3dD_f$</td>
<td>1.69</td>
<td>1.94</td>
<td>2.33</td>
<td>1.86</td>
<td>2.16</td>
<td>1.89</td>
<td>1.78</td>
<td>1.89</td>
<td>1.99</td>
</tr>
</tbody>
</table>
2.7.2 Electrical Tree Types

Branch trees and bush trees, previously displayed in Figure 1-6 (a) and (b), are the basic tree types (fine trees are discussed in the following section). Usually branch trees grow faster than bush trees [25] and tree shapes are affected by various factors under AC stresses. Bush trees usually exist at higher voltage magnitude while branch trees usually form at lower voltage magnitude [42][107][110]; bush trees are also found in older glassy epoxy (glass transition temperature $T_g$ higher than room temperature) samples [111]; higher temperatures (90 °C) are reported to give rise to branch trees in XLPE regardless of voltage magnitude [112]. Voltage frequency affects tree shapes by lowering the transition voltage from branch trees to bush trees at frequencies higher than the utility frequency [25]. Bush-branch trees, previously displayed in Figure 1-6 (c), usually appear in samples with bigger tip-plane distance at higher voltages or with higher frequencies [26][30][47]. Bush trees are also reported to appear in EAA (ethylene acrylic acid copolymers) samples with frequencies lower than the utility frequency while the same voltage at the utility frequency leads to branch trees [95].

Besides these three tree types (bush, branch and bush-branch), other words have been chosen to describe tree shape variations, as shown in Figure 2-45: pine in LDPE and XLPE, i.e. ‘pine-needle’ in (a) [42] and ‘branch-pine’ in (b) [107]; bine in XLPE, i.e. ‘branch-bine’ in (c) [107], and ‘monkey-puzzle’ in flexible epoxy ($T_g$ lower than room temperature) in (d) [110]. The branch-bine structure in Figure 2-45(c) is considered to be the monkey-puzzle in Figure 2-45(d) [113], which seems to make sense considering both feature short side branches on both sides of main channels. Though the classification of branch, bush, pine and bine is based on morphology, differences relating to channel conductivity and PD activity can be found within these channels.
Tree growth is considered to be closely linked to partial discharges within tree channels and the conductivity of tree channels. It has been suggested that it is the disordered graphitic carbon residues (according to Raman spectroscopy) on tree channel walls, which might be decomposition products from PD, that increases the conductivity of tree channels [114] and that the conductivity in turn changes PD patterns associated with the tree channels [96][115]. Figure 2-46(a) shows the location of various spots in a branch-pine structure: A is at the centre of a black channel, the other two are chosen at 1 µm (still inside the channel) and 12 µm (outside the channel, indicating the XLPE base) away along the bare arrow line end; D peak of ~1560 cm\(^{-1}\) and G peak of ~1360 cm\(^{-1}\) were found at the two spots inside the channel in Figure 2-46(b) [113]. These two peaks are the signature of graphitic carbon and based on G peak strength the number of graphite layers or the thickness of the carbon decomposition can be calculated [116] and the thickness was reported to be less than 10 nm in conducting tree channels [114][117].
Figure 2-46 Raman spectra at various spots (bare end of arrow line is $A$, indicating 0 $\mu$m, 1 and 12 $\mu$m is spots 1 and 12 $\mu$m away from $A$ along arrow line) [113]

Figure 2-47 shows a bush tree structure with reflected light. Black channels are only found in a small area in front of the needle tip and the main body comprises transparent channels [117]. D peak and G peak were found at 21 $\mu$m in front of the needle tip corresponding with the black channels in Figure 2-47 (a), while no such peaks appeared at 1320 $\mu$m away from the needle tip corresponding with the transparent channels in the main body in Figure 2-47 (b). The thickness of carbon decomposition was also less than 10 nm. Raman spectra in the transparent channels in branch trees also showed no D and G peaks [117]. Therefore, channel images with reflected light help to tell whether channels are non-conducting (transparent channel images) or conducting (black channel images).

Figure 2-47 Bush tree structure image with reflected light [117]
Light emission distribution from PD is another tool commonly employed to help understanding channel conductivity, as shown in Figure 2-48 [115]. The light emission distributes along main channels in a non-conducting tree while it is only spotted at channel tips in a conducting tree because the high conductivity of the channel walls facilitates PD propagating from near the needle tip to channel tips and therefore no local electron avalanches within channels [115].

![Figure 2-48 Light emission from PD of (a) non-conducting and (b) conducting channels [115]](image)

In summary, in polyethylene conducting channels are usually found in the black channels in the pine and bine structure which forms at relatively low voltages while branch and bush trees which form at higher voltages usually lead to non-conducting trees in the main body, though conducting channels can be found in the black channels close to the needle tip [42][117]; in epoxy resins non-conducting channels are usually found in flexible epoxy while conducting channels in glassy epoxy [115].

The relation between channel conductivity distribution and PD is a dynamic process. Conducting channel walls or conducting regions in partially conducting channels facilitate PD propagation towards channel tips, gradually change the conductivity along channels by PD erosion and the space charge distribution along channels, and this leads to local electric field enhancement at tree tips caused by homo space charges accumulated in the same positive or negative half cycles, which in turn decreases the effective electric field from the needle tip to tree tips and in the end suppresses PD magnitudes and PD activity [96]. Therefore, low magnitude PD events with turtle-like PRPD pattern are also used as an indicator of conductivity with proper context, as shown in Figure 2-49(b), whereas quite high magnitude PD events with wing-like pattern
appear in non-conducting channels, as shown in Figure 2-49(a). By proper context, it is meant that non-conducting channels can develop into conducting one with PD erosion over time. Figure 2-49 are actually PRPDs of (a) 1470-1490 s and (b) 7120-7140 s from one sample and combined with the PD light emission images during the same period in Figure 2-50 (b) and Figure 2-50 (d) respectively, it is reasonable to relate PD activities to channel conductivity.

![Figure 2-49 PRPD pattern of (a) non-conducting and (b) conducting trees [42]](image)

![Figure 2-50 Tree images and localisation of light emission over the 20 seconds in Figure 2-49 [42]](image)

### 2.7.3 Fine Tree and Reverse Tree in Glassy Epoxy

There is another distinct tree structure called ‘filamentary tree’ or ‘fine tree’ occurring in glassy epoxy resins under pure 50 Hz AC [118]. Compared with branch trees and bush trees (2 µm and 3-4 µm in diameter respectively [109]), fine trees have channels of relatively small diameter of less than 1 µm. They could develop either from initial dark tree structures as shown in Figure 2-51(a) or directly from the needle tip as shown in Figure 2-51(b). These fine channels continue growing until either partially extending to
the ground electrode followed by darkened channel tips near the ground as shown in Figure 2-51(c) or completely bridging the ground as shown in Figure 2-51(d). Following this are ‘reverse trees’ in many though not all the samples, which features growth from ground electrode back towards HV needle electrode through some of the existing fine channels. Though the mechanism of reverse tree formation is not clearly known, it is considered to be a combined result of many factors, such as epoxy post-curing arrangement (with or without the PMMA mould into which the epoxy and the hardener was previously cast) and ambient experimental conditions (sample in air or silicone oil). Fine channels are always to be a precursor of reverse tree growth [118].

Figure 2-51 Fine channels from (a) existing dark channels or (b) needle tip; reverses trees in red after fine channels (c) partially extending to or (d) completely bridging ground electrode at 15 kV pk AC in glassy epoxy resin (r = 3 µm, d = 2 mm) [118]
In cases without reverse tree development, fine channels and dark channels were found to grow simultaneously prior to sample failure through one of dark channels, as shown in Figure 2-52 (r = 3 µm, d = 1 mm) [119], where dark channel growth was accompanied with detectable PDs and therefore labelled as PD tree in the figure, while fine channels were thought to be electrofractures driven by electromechanical process.

Figure 2-52 Fine tree at 15 kV pk AC and PD tree growing simultaneously prior to sample failure through red dashed line (glassy epoxy, r = 3 µm, d = 1 mm) [119]

Figure 2-53 shows the relation between tree images and PD activity from voltage application to sample failure [120]. Stage 1 is an incubation stage before tree initiation when there were no PDs larger than 0.35 pC which was the PD measurement sensitivity. Stage 2 describes the growth of initial dark tree structures which were accompanied with PDs that could reach up to ~35 pC. Stage 3 records fine tree channel propagation from the initial dark channels to ground while PD magnitudes dropped dramatically to, and then remained at, ~0.4 pC. It would be not sensible to assume fine channels are conducting merely based on the fact that PDs are of fairly low magnitudes during this stage, because the context does not indicate any possibilities of PD erosion in these fine channels before this stage. Stage 4 features channel darkening of fine tree channels after some of them partially extended to ground, with PD magnitudes increasing slightly to ~1.0 pC. Stage 5 is reverse tree growth and divided into three sub-stages: in Stage 5.1 there was evident reverse channel growth in the image and PD magnitudes also rose to ~350 pC which was ten times of the maximum magnitude in initial dark tree growth in Stage 2; Stage 5.2 is when reserve trees stopped growing with PDs in the range of 0.4~0.6 pC and Stage 5.3 records the time period before sample failure with sporadic PDs in the range of 1.3-900 pC.
‘Fine channels’ was also chosen to describe channels of ~ 1 µm in diameter grown under AC fields in LDPE as shown in Figure 2-54, though the image quality is not satisfactory, especially in (b). However, no reverse trees were reported in both cases [26][30].

2.7.4 Tree Growth under Pure DC Stresses

Though tree initiation is much more difficult with pure DC stress, tree growth has been investigated under continuous DC stresses with AC pre-initiated trees in epoxy resin [45] and under periodic DC stresses with initiation by grounding in XLPE [121].
The length of inceptive AC trees (L_{IT}) was found to play a critical role in the subsequent DC tree growth [45]: little tree growth was observed with ten-hour voltage application at +60 kV when L_{IT} < 33 µm and at -60 kV when L_{IT} < 45 µm. These two critical values were thought to be closely related to the area with the moderated local electric field under DC stresses which are caused by homo space charge injection and accumulation around the needle tip. L_{IT} needed to be long enough in the first place to ensure it extended beyond the moderated area to result in further tree growth under DC stresses as shown in Figure 2-55(b), otherwise the inceptive channels would be kept enveloped in the area with well moderated field which would not lead to further growth as shown in Figure 2-55(a). The critical length of 45 µm at -60 kV being longer than that of 33 µm at +60 kV also indicates that for space charge injection electrons travel further than holes, which is in good agreement with negative short-circuited tree length being longer than the positive length at various voltages shown in Figure 2-24 in Section 2.3.3.

The tree shape grown under DC stresses was found to be a branch structure shown in Figure 2-56 [45], which had many fewer branches compared with the branch structure under AC stresses. Moreover, trees grown under +60 kV were longer and tended to result in tree channel runaway and consequently sample failure, while that under -60 kV growth was self-limiting in length and all shorter than 25 % of the tip-plane distance.
after ten hours [45]. It should be noted that no DC ramp up rate was mentioned in the paper.

![Image](image1.png)

**Figure 2-56** Tree structure at (a) +60 kV and (b) -60 kV with inceptive AC trees in inserted boxes [45]

Periodic DC shown in Figure 2-57 was applied to XLPE samples after grounding tree initiation with length less than 30 µm: one cycle included increasing DC to $U_{set}$ (+50 kV and -70 kV) at 1 kV/s and holding for 30 min before decreasing DC at 2 kV/s which was followed by 15 min waiting time at zero DC [121]. It was found that considerable tree growth occurred during DC rising processes compared with little growth during the 30 minutes of steady DC voltage in both polarities and longer channels and sample failure were also found under positive DC even though the absolute value of negative DC was 20 kV (40%) higher. The difficulty in generating further growth with periodic negative DC is consistent with that at continuous negative DC shown in Figure 2-56.

![Image](image2.png)

**Figure 2-57** Periodic DC voltage profile applied to pre-initiated XLPE in [121]

Trees stressed by positive DC either failed during the first time of DC rising or reached more than 50% of the tip-plane distance after at most four cycles, while 9 out of 10 samples at negative DC were reported to have further grown during the first time of DC...
rising but all have disappeared in the steady DC stage after 1-3 cycles. This was called self-healing. Relevant images from the paper are displayed in Figure 2-58 and no convincing mechanism for self-healing was given. One exceptional sample under negative DC reached 50% of the dielectric gap in the 8th cycle, growing much more slowly than trees under positive DC.

![Figure 2-58 Self-healing phenomenon in periodic negative DC reported in XLPE [121]](image)

Self-healing of electrical tree channels has been reported previously in polymers, but only with special material designs: superparamagnetic nanoparticles with surface functionalisation were embedded into polymer before treeing aging; then the aged sample was exposed to an oscillating magnetic field; the field would lead to the migration of the functional nanoparticles and result in local healing, which eventually healed tree channels [122].

### 2.7.5 Tree Growth in DC plus AC Fields

Among the 5-stage growth in epoxy resin shown in Figure 2-53, stage 5 of reverse tree growth was reported not to exist in samples when the AC voltage was superimposed with DC voltage in either polarity and therefore considerably shortened time to breakdown [120], as shown in Figure 2-59 where samples were initiated with pure AC voltages (8.5-17.0 kV pk) and grew under voltage superimposition. Though reverse tree formation is not well known, voltage type can be safely considered as one of many factors which would determine reverse tree growth. With DC superimposition, the
electric field distribution between the needle tip and plane electrode might be changed considerably compared with pure AC stresses, which might as a result lead to channel breakdown rather than reverse trees. Moreover, it should be noted that 15 kV pk AC is well above tree initiation voltage in pure AC fields and that the DC component of ±15 kV was quite low considering that hours or even days were required for tree initiation at +60 kV and initiation was never observed at -60 kV applied to samples with the same geometry.

However, it was reported that the superimposition of +15 kV DC onto 15 kV pk AC in LDPE leaded to quicker breakdown in bush trees whereas that of -15 kV DC prolonged time to breakdown [42], as shown in Figure 2-60. Again, in this case 15 kV pk AC is well above tree initiation voltage in pure AC fields and that the DC component of ±15 kV was quite low with the same geometry which will be discussed in Chapter 4 and Chapter 5. Other conclusions on tree growth in DC plus AC superimposition fields from [42] include +20 kV DC superimposed onto 10 kV pk AC gave rise to a more bifurcated structure in tree initiation without affecting initiation time significantly, while -20 kV considerably accelerated initiation, and +12, +15, +18 kV DC superimposed onto 12 kV pk AC also accelerated branch tree growth.
PD signals were described in detail in [42] and classified into ‘Stable PD’ and ‘Transient PD’ based on PD magnitude in both polarities, $Q_{pk}(+q)$ and $Q_{pk}(-q)$ hereafter, and PD number in both polarities, $N(+q)$ and $N(-q)$ hereafter, where positive PD events usually occur in voltage rising half cycles (0°-90° and 270°-360° in phase angle) and negative ones usually occur in voltage dropping half cycles (90°-270° in phase angle). Figure 2-61 displays PRPD patterns in (a) and (b), and histogram plots of PD events over phase in (c) and (d) of both PD types. Stable PD refers to the case in Figure 2-61(a) and (c) where $Q_{pk}(+q) > Q_{pk}(-q)$ and $N(+q) < N(-q)$; transient PD refers to the case in Figure 2-61(b) and (d) where $Q_{pk}(+q) \leq Q_{pk}(-q)$ and $N(+q) \geq N(-q)$.

Figure 2-61 Example of ‘Stable PD’ (a and c) and ‘Transient PD’ (b and d) in a 12 kV pk pure AC treeing test [42]
These two types of PDs were found to have occurred in tests at 12 kV pk AC with and without DC components resulting in branch tree structure and at 15 kV pk AC with and without DC components leading to bush tree structure. However, 15 kV pk AC gave rise to pronounced differences in PD number per cycle and the symmetry between positive PDs and negative PDs, as shown in Figure 2-62(a). It can be seen from the figure that PD number per cycle increased with negative DC bias and decreased with positive DC bias and that the difference between number of positive PDs and that negative PDs was more pronounced with negative DC bias while became less with positive DC bias. Moreover, the fraction of the stable PDs was also affected by ±15 kV DC bias on 15 kV pk AC, as is shown in Figure 2-62(b). It was explained to be affected by space charge behaviour around tree channels, which is illustrated in Figure 2-63.

![Figure 2-62](image1.png)

**Figure 2-62** a) Comparison of mean PD number per cycle and b) fraction of stable PD over entire growth time period by polarities in bush trees in LDPE (r = 3 μm, d = 2 mm) [42]

![Figure 2-63](image2.png)

**Figure 2-63** Illustration of space charge behaviour in fields with 15 kV pk AC [42]
Under pure AC fields, as shown in Figure 2-63(a), negative PDs inject electrons into tree channels and in the subsequent positive half cycles de-trapping of electrons from tree tips (hollow circle in figure) could occur to form positive PDs while there are still negative space charge accumulation in the front of the tree, which is similar to space charge transfer between metallic needle and polymer base in Figure 2-25. With negative DC component, to form a waveform right below the zero-axis line, as shown in Figure 2-63(b), the likelihood of more electron injection to incept electron avalanche (i.e. negative PDs) is increased while positive DC component to form a waveform right above the zero-axis line, as shown in Figure 2-63(c), generates positive space charges and reduces the likelihood. Therefore, more negative PDs and stable PDs were seen to exist with -15 kV DC bias while +15 kV bias resulted in lower percentage of stable PDs.

There are several other papers discussing tree growth under DC superimposed on AC stresses. It was reported that 1) after grounding tree initiation, a positive DC component (+10, +20, +30 kV) superimposed on 10 kV pk accelerated tree growth in XLPE, and with a -30 kV DC component, 15 kV pk AC component leaded to a branch-pine structure while 10 kV pk AC component gave rise to a bush structure [55] and that 2) a -12 kV pk DC component tended to form a bush structure and more accumulated damage with a 12kV pk AC at 150 Hz in epoxy resin without information on initiation [123].

2.8 Voids and Air Gaps on Treeing in AC Fields

This section includes the work on voids (or artificial air gaps) and naturally formed air gaps around the needle tip in electrical treeing in AC fields to highlight the role of metal-polymer interface and the partial discharges in treeing. It was the collaborate output in the early stages of this project when the author was actively involved. Some of this work has been published [53][124] and some is in the writing process.

Voids refer to the artificial air gap formed in LDPE by extracting the needle partially from inside the sample and therefore result in a needle shape. The depth or the height of the
void is defined as the vertical distance from the needle tip to the void tip. Compared with the needle-shaped voids which has been investigated (500-2000 µm in height) [47][103][125], smaller void heights (100-250 µm), as well as an air gap free sample and an sample with a void of ~1000 µm, were included in our work. It was discovered that PDs could develop in these voids prior to tree initiation, which, instead of the void size, in turn affected treeing in pure AC fields. In the air gap free sample, the PD magnitude was found to increase with the tree length, while corona discharges were identified based on the light emission by PDs within the voids and tree channels and PRPD patterns in samples with voids. Branch-typed trees were initiated from all the samples at 12 kV pk AC, however, they had different subsequent growth which was thought to attributed to discharges within the voids. The sample with a 115 µm void which had higher magnitude streamer discharges in the void was found to have the quickest growth rate and the shortest time to sample failure. In samples with larger voids of 212 µm and 1037 µm but with lower PD magnitudes over the whole treeing time, tree structures ceased propagation in length after the rapid extension in the early stage and eventually developed into a pine-branch structure which is thought to be conductive [126]. That the conductive channels supresses PD activity [96] also agreed with the lower PD magnitudes in both samples.

Besides the needle-shaped voids, air gaps can form naturally in front of the needle tips. In this case the gap height cannot be read accurately from optical images. It was determined to be of 10-55 µm in height, with the access to XCT technique which will be detailed in Section 3.2. Before this project, no such tiny air gaps with the accurate height have been reported and investigated. These optically invisible gaps also affect tree initiation and growth in AC fields mainly by the mechanism of partial discharge variation within the air gaps in both incubation and tree growth period, rather than the air gap size [53]. The existence of the air gap and the discharges within the gap did not necessarily lead to quicker initiation; however, the relatively large and frequent PDs during the incubation period usually resulted in a more branchy structure than in gap
free samples and samples with air gaps but accommodating weak PDs. More details with specific samples can be found in [53], and the key guidance from this work is that the metal-polymer interface can vary from sample to sample and the PD measurement with a high sensitivity is a powerful tool to understand the nature of the interface in specific cases. Also, if PD sensitivity requirements cannot be met for some reason, sample quality control is critical to reproducible results which will in turn yield more sensible understanding of treeing.

2.9 Summary of Literature and Research Gap

This chapter begins with electrode systems to initiate electrical trees in laboratories and focuses on the needle-plane geometry. Different voltage types are found to initiate trees, as well as in the superimposed fields of different voltage types. Space charge from the needle tip to the polymeric base is thought to have the crucial role in tree initiation. Physical and chemical phenomena, for example electroluminescence and free radical formation, prior to tree initiation are introduced. Based on these phenomena, some theories on tree initiation have been proposed, such as degradation by space charge injection & extraction, photodegradation by electroluminescence, electromechanical cracking, and local intrinsic breakdown. The topic of partial discharges is elaborated, including PD measurements and the relation between PD activities and tree channel conductivity and thus tree growth.

Typical tree types are also discussed in this chapter, which includes branch trees, bush trees, and bush-branch trees. Fractal dimension ($D_f$) is a parameter to describe different tree structures and bush trees have a higher $D_f$ than branch trees. However, for complex and dense tree structures, a 3D $D_f$ reveals the complexity better than a 2D $D_f$. Filamentary trees (fine trees), which is of ~1 mm in channel diameter and do not support PD activities, and reverse trees in glassy epoxy are also reviewed. Tree growth under pure DC stresses but with AC inceptive initial trees is affected by the initial defect length and shows polarity dependence. The initial length must be longer than a ‘threshold’
length to have tree growth under pure DC stresses and positive DC leads to longer channel propagation while negative DC results in a short and self-limiting growth. Tree growth under periodic DC voltages with short-circuited initiation shows consideration growth during DC ramp up and little growth during steady DC stresses. Treeing under DC stresses superimposed with AC voltages is material dependant and voltage magnitude dependant but is closely associated with space charge accumulation and distribution in the polymeric insulation. This chapter also discusses the effect of microscopic air gaps and needle-shaped voids on treeing and founds PDs in the air gaps or voids plays a key role in tree initiation and growth.

Though it has been reported that a higher voltage magnitude is required for tree initiation in pure DC fields than in AC fields and in negative DC fields than in positive DC fields, not many details on tree initiation (such as initiation times) and the sequent growth under pure DC voltages has yet reported. In the early years of treeing research, PD measurement techniques were not well developed and employed in the relevant research. Moreover, crosschecking the experimental results of electrical treeing, including initiation and growth in DC plus AC fields reviewed in Section 2.2.4 and 2.7.5, contrary and sometimes apparently conflicting conclusions can be spotted. This is actually because not only the ratio of AC to DC in the superimposition (\(R_{AC/DC}\)) is different in different insulation materials in different research but the ratio of AC component to AC initiation voltage (\(R_{AC/ACi}\)) and that of DC component to DC initiation voltage (\(R_{DC/DCi}\)) are also different. In those papers \(R_{AC/DC}\) and \(R_{AC/ACi}\) could be larger than 1.0 while \(R_{DC/DCi}\), on the contrary, was quite small. Different treeing phenomena in DC fields and in AC fields indicate that there might be very different initiation and growth mechanisms for both. With various \(R_{AC/DC}\), \(R_{AC/ACi}\) and \(R_{DC/DCi}\) in the voltage superimposition it is very hard to tell how the space charge would behave and which mechanisms might play a dominating role, let alone in most cases DC tree initiation voltages were unknown (therefore \(R_{DC/DCi}\) is unknown) and the AC component was usually set higher than AC tree initiation voltage to accelerate treeing. Bearing this in mind, it is not surprising to spot
contrary conclusions (explained D7: **Apparently contrary conclusions in DC plus AC fields**). $R_{AC/DC}$ and $R_{AC/ACi}$ being larger than 1.0 while $R_{DC/DCi}$ being quite small cannot represent working conditions of the insulation system in HVDC transmission networks, where the AC harmonics are usually generated from converters in HVDC links and of small amplitudes compared with the operating DC voltage level in individual networks [11][127].

In order to better represent working conditions of the insulation system and reveal how power quality affects electrical treeing in HVDC links, very high DC voltages equal or close to DC initiation voltage superimposed variations in power quality are required. This project will investigate the role of long-term power frequency ripple on DC ageing. Treeing under pure DC stresses and PD measurements will be also included in all the treeing tests in this project. Experimental details of this work are presented in the next chapter.
Chapter 3  Experimental Description

The main aim of this project is to initiate electrical trees and evaluate and analyse tree growth in low-density polyethylene (LDPE) in pure DC fields and under DC stresses superimposed with AC ripples, with positive and negative polarities of DC included. Tree initiation and growth images are captured by a CCD camera and PD signals with phase information are also recorded. XCT is employed as the tool to reconstruct tree structure three-dimensionally.

3.1 Sample Fabrication

3.1.1 Thermoplastic Samples

Commercial LDPE slices (300 mm x 300 mm x 3.18 mm) purchased from Alfa Aesar have been employed in this project to fabricate treeing samples. The density is 0.945 g/cm³ at 20 °C. The melting range is 104-138 °C and the autoignition temperature is 343°C. The product SDS file is attached as Appendix I. The slice was first cut into small blocks of 30 mm x 20 mm x 3.18 mm. Figure 3-1 illustrates the apparatus for making needle-plane treeing samples made of thermoplastic materials, taking a 30 mm x 20 mm x 3.18 mm LDPE block as an example. The main part shown in Figure 3-1(a) is the metallic three-block structure with one block (illustrated in light green) shaped to host the LDPE and the other two (in light orange and light yellow) to encapsulate the LDPE. The light green part can be replaced by blocks machined into different shapes and thicknesses to host, for example, XLPE cables. Then the structure with the LDPE block inside is placed into the assembly shown in Figure 3-1(b). A recycled or previously used needle is firstly fixed by a bolt into the upper sliding part to make a hollow pre-hole in the LDPE block by hand before a brand-new needle is fixed and enters the hole without additional external force. In this way, the needle tip will not be forced against the end of the hole until the temperature is increased with only the gravity of the upper sliding part (weighing 190 g) pushing downwards, therefore protecting the tip. The steel needle used here is from
Ogura® and of 1 mm in trunk diameter with a 30° taper and 3 µm tip radius. Then the assembled mould, together with the needle, are kept in an oven at 120 °C for 2 hours to soften the LDPE. As a result of the material being softened, the needle gradually moves downwards with the upper part sliding into the LDPE and the sliding part meets the three-block structure. After a timer switches the oven off, the mould remains in the oven to cool down to room temperature.

Figure 3-1 Kit for fabricating the needle-plane treeing sample made of a thermoplastic material.

The ~2 mm separation (2.23 ± 0.23 mm) between the needle tip and the bottom of the LDPE block (needle-plane distance) is ensured by the geometrical design of the mould itself and the following process: 1) as shown in Figure 3-2(a), place the upside-down upper sliding part on top of a spacer with a hole, which comes with the mould and is illustrated in Figure 3-2(b), 2) fasten the needle in position, 3) place the sliding part back into the mould as shown in Figure 3-1(b), and 4) the needle-plane distance is ~2mm when the sliding part meets the three-block structure in the oven at 120 °C.
To assess the temperature variation of LDPE samples in the oven, a thermocouple shown in Figure 3-3 (RS Pro Type K 363-0250 with a temperature range from -75 °C to 250 °C), instead of a brand new needle, was placed into the pre-hole and assembled into the mould. The mould was then kept in the oven set at 120 °C for 2 hours and left inside overnight to ensure the thermocouple was cast into LDPE and cooled down to room temperature. The thermocouple was then connected to a digital multimeter (Tenma 72-8720) and the two-hour 120 °C heating cycle was repeated to record the thermal information. Figure 3-4 is the thermal curve showing that a full cycle of one sample takes around six hours.
Figure 3-5 shows photos of the moulds. In Figure 3-5(a) the outlined 110 µm thick PET films on each side of the green block illustrated in Figure 3-1 and the kitchen foil at the bottom are employed for the convenience of releasing the treeing sample from the three-block structure after the heating-up mentioned above; Figure 3-5(b) is the other mould with adjustable tip-plane distance depending on the height of the spacer and the rectangle outlined by the dashed line is of 30 mm x 21 mm to hold the sample. An aluminium tape will be attached to the sample bottom to ensure secure electrical contact between the sample and plane electrode.

![Figure 3-5 Photo of (a) mould with 2 mm without the light orange block shown in Figure 3-1(a)](image)

Figure 3-6 is a photo of a typical LDPE treeing sample with breakdown channels under pure AC stresses. The transparency level required for imaging explains why the thickness of 3.18 mm was selected for tree initiation observation.

![Figure 3-6 LDPE treeing sample (30 mm x 20 mm x 3.18 mm) with breakdown channels under pure AC stresses](image)
3.1.2 Thermosetting Samples

The epoxy treeing sample shown in Figure 3-7 has long been investigated [8]. It has also been fabricated to test the circuit performance before tests on LDPE, considering previous experience with epoxy resin can provide a good guidance to this project. Epoxy resin, as a thermosetting material, has a totally different sample fabrication procedure from LDPE. Epoxy resin sample fabrication includes 1) mixing of epoxy resin and its hardener, 2) mixture degassing, 3) room temperature curing, 4) post-curing at a higher temperature, and 5) aluminium evaporation on the bottom of the sample. There is an elaborate description of material properties and procedure to fabricate epoxy resin treeing samples in [8], therefore it is not detailed here.

![Figure 3-7 Dimension of epoxy resin treeing samples [8]](image)

3.2 Air Gap Detection

Due to the fact that the thermal expansion coefficient of the metallic needle is different from that of the polymer, a gas phase or an air gap might be introduced naturally to the metal/polymer interface in laboratory treeing samples. Naturally formed air gaps, though tiny in size, affect tree initiation and the subsequent growth in LDPE in AC fields [53]. Moreover, it has also been reported that 5-15 µm air gaps affect treeing in silicone rubber in DC fields, though the size of air gaps was estimated by optical images [128], as shown in Figure 3-8. Therefore, fabricated samples in this project were examined to
ensure that there were no air gaps around the needle tip before connected to high voltages for tree initiation.

![Figure 3-8 Optical images of (a) normal sample and (b) air gap sample [128]](image)

### 3.2.1 Optical Observation

An air gap can be identified by optical observation only when it is large enough and leads to an apparent shape change in front of the needle tip, as shown in Figure 3-8(b) and Figure 3-9(b) which was fabricated at 100 °C, compared with Figure 3-9(a) fabricated at 120 °C. As at 100 °C the upper sliding part (weighing 190 g) needed external force to meet the three-block structure in the mould [53], the formation of the sharper air gap is thought to be a consequence of the external force. However, the accurate height of the air gap cannot be measured from the picture, because it is not easy to locate the needle tip (as opposed to the air gap tip) in Figure 3-9(b).

![Figure 3-9 Optical LDPE pictures of (a) a normal shape in front of needle tip fabricated at 120 °C and (b) an air gap leading to an apparently sharper and extended needle tip fabricated at 100 °C.](image)
Chapter 3: Experimental Description

### 3.2.2 2D Radiographs by XCT Technique

X-ray Computed Tomography (XCT) is a non-destructive technique which generates images (also known as radiographs or projections) by measuring the transmission of X-rays through a solid object to show its interior features. There are three typical components in an XCT system, as shown in Figure 3-10: 1) a source which generates X-rays to form an X-ray beam, 2) a rotation stage to which the object is attached, 3) a detector which collects and counts the X-ray signals which travel through the object. The X-ray attenuation during that process is a function of X-ray beam energy, the nature of the beam path (such as the path length and the medium of the path) and the density and composition of the subject which is scanned [129]. The 2D radiograph displays the X-ray transmission density through the object in grey scale: the larger the grey value (the lighter the image looks), the less the attenuation and the more transmission of the X-rays, therefore the higher radiation intensity the detector receives; the darker the image looks, the less radiation intensity the detector receives.

![Figure 3-10 Schematic diagram of how XCT equipment works.](image)

In order to evaluate the sample fabrication procedure and quantify the air gap where there is one, both micro-XCT (Xradia 520 Versa, Zeiss) and nano-XCT (Xradia 810 Ultra, Zeiss), which are available at Henry Moseley X-Ray Imaging Faculty, the University of Manchester, were used in this project. Some technical specifications of micro-XCT are listed in Table 3-1 and of nano-XCT in Table 3-2. More details can be found on Zeiss websites [130][131].
Table 3-1 Technical specifications of Micro-XCT [130]

<table>
<thead>
<tr>
<th>Model</th>
<th>Xradia 520 Versa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>0.7 µm</td>
</tr>
<tr>
<td>Minimum achievable voxel</td>
<td>70 nm</td>
</tr>
<tr>
<td>Tube voltage range</td>
<td>30-160 kV</td>
</tr>
<tr>
<td>Maximum output</td>
<td>10 W</td>
</tr>
<tr>
<td>Objectives</td>
<td>0.4x, 4x, 20x, 40x</td>
</tr>
</tbody>
</table>

Table 3-2 Technical specifications of Nano-XCT [131]

<table>
<thead>
<tr>
<th>Model</th>
<th>Xradia 810 Ultra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>50 nm</td>
</tr>
<tr>
<td>Field of view</td>
<td>16 µm</td>
</tr>
<tr>
<td>Voxel size</td>
<td>16 nm</td>
</tr>
<tr>
<td>Magnification</td>
<td>800x</td>
</tr>
<tr>
<td>X-ray photo energy</td>
<td>5.4 keV</td>
</tr>
<tr>
<td>Voltage</td>
<td>35 keV</td>
</tr>
<tr>
<td>Power</td>
<td>0.9 kW</td>
</tr>
</tbody>
</table>

Figure 3-11 compares images captured by both nano-XCT and micro-XCT of the same sample. Metals exhibit higher X-ray attenuation coefficients compared with polymers, which leads to less transmission and lower received intensity of X-rays resulting in the darker area in Figure 3-11.

The slightly bright band enveloping the needle tip in Figure 3-11(a) is due to either a real low-density phase that might exist between the needle tip and the LDPE base or a feature of the phase contrast process which is designed for low-attenuation materials such as polymers. Edge enhancement features in phase contrast process [129], an example of which is shown in Figure 3-12 [132]. The Xradia 810 Ultra has a physical phase...
ring in the beam path to produce phase contrast [131], hence it is highly likely that phase contrast is the reason for the band. The thickest width of the band measured by nano-XCT was ~0.8 μm, which was not detected in Figure 3-11(b) by the Xradia 520 Versa of which the spatial resolution is 0.7 μm at its best [130].

![Figure 3-12 An example of edge enhancement (where red arrows point in (b) compared with (a)) featuring phase contrast [132]](image)

Considering that micro-XCT has a sufficiently high resolution, and that samples for nano-XCT detection must be machined and polished into a very small size which is no longer suitable for treeing tests, as shown in Figure 3-13, only 2D radiographs by micro-XCT have been used to detect whether there exists an air gap at the needle tip. In addition, even if the band mentioned above in nano-XCT detection was a low-density phase, it might have been introduced by the process of polishing the sample from its original size in Figure 3-6 to what is shown in Figure 3-13.

![Figure 3-13 Sample size requirement for nano-XCT](image)

Four more examples by micro-XCT are shown in Figure 3-14: the first one is detected to have an air gap of ~4 μm, the second one has no air gaps but has a needle tip defect, the
third one is free of air gaps with a perfect needle tip and the last one is the sample in Figure 3-9(b) of which the gap height is not available in the optical image. Therefore, it is reasonable to believe that air gaps larger than \(~4 \mu m\) are detectable by micro-XCT and air-gap-free samples in this project are ones free of micro sized air gaps unless noted otherwise.

![Image](image.png)

**Figure 3-14** Radiographs of samples (a) with a \(~4 \mu m\) air gap, (b) with tip defect, (c) without air gap and (d) with a \(~35 \mu m\) air gap by Micro-XCT; (d) is the sample in Figure 3-9(b); scale bar applies to all.

120°C was experimentally determined to be sufficiently high to soften an LDPE block for needle insertion without damaging the needle tip. Leaving the treeing sample inside the oven till it reached the room temperature after the timer switched off led to a gradual cooling process, which reduced the probability of the air gap formation. To clarify, Figure 3-15 displays the radiographs of needle tip damage and air gaps in samples fabricated at 110 °C and 100 °C when air gap formation was investigated in the early stage of this project. The number of samples with air gaps to ones without air gaps was 2:9, 2:7 and 3:1 when needle was inserted at 120 °C, 110 °C and 100 °C respectively [53]. The probability of both air gap formation and needle tip damage reduced to two or three out of thirty at 120 °C with more sample fabrication experience. In terms of sample transparency, keeping the treeing sample inside the oven till the room temperature is also of great importance. This controls cooling in the critical temperature range regardless of ambient temperature. The cooling process dominates the crystalline morphology, for example grain size and the crystallisation rate, of LDPE [133] which determines the boundaries between crystalline and amorphous regions in a polymer.
Light scattering on these boundaries, and thus light being transmitted through the polymer, governs its opacity [134].

![Figure 3-15 Needle tip damage and air gaps at lower fabrication temperatures [53]](image)

### 3.3 3D Imaging of Electrical Trees

In addition to capturing 2D radiographs, the XCT technique can be further employed to do 3D imaging of electrical trees in LDPE. Our group has established a systematic output of 3D imaging of electrical trees in epoxy resins, above or below the glass transition temperature, pure resins or resins with micro-sized fillers [108], [109], [135]–[138]. This project took advantage of the Xradia 520 Versa and reconstructed the tree structure growth under negative DC superimposed with AC ripples because of its novel geometric characteristics seen optically.

For 3D imaging or volume rendering, a series of 2D radiographs is taken while the object is rotating on the sample stage over at least 180 degrees; the X-ray radiation intensity profile of the radiographs at different angles in a given sectional plane generates back projections which are to be superimposed to form the image of the sectional plane; then the volume rendering is obtained by piling up the sectional planes. Taking a solid cylinder containing a smaller hollow one sharing the same central line in Figure 3-16(a) as an example, a sectional plane is extracted and the transmission density profile against position is displayed in Figure 3-16(b). Based on this, the back projection at a certain angle is obtained shown in Figure 3-16(c); as the object rotates, different back projections can be obtained from different angles and then the image of the sectional plane forms when the back projections are superimposed, as shown in Figure 3-16(d);
this process is repeated for each sectional plane resulting in volume rendering. Better images and volume reconstruction can be achieved with more back projections and proper filters and algorithm.

Figure 3-16 Diagram of how to obtain image of a sectional plane in volume rendering.

3.4 Sample Protection from Potential Surface Creepage Currents

Since high DC voltages were employed under positive DC superimposed with AC ripples to initiate a tree, the presence of a very high electric field was expected, which may bring about some issues which never occurred under lower pure AC stresses. For example, in some cases the sound of discharges was heard during tests either in the process of the DC voltage being raised from 0 kV to the targeted value (occasionally when the voltage was held at the targeted value) or at the moment an initiated tree was captured by a
CCD camera. One possible cause was thought to be creepage along the sample surface from the high potential needle trunk to the grounded electrode due to the existence of the high electric field, even though the whole sample together with the needle was submerged in silicone oil. The most likely path was believed to be along the red solid arrowed lines in Figure 3-17, because it was the shortest path exposed in the oil from the high potential needle trunk to the ground. Therefore, a simple protection shown in Figure 3-18(a) was employed to deliberately replace the shortest path illustrated in red in Figure 3-17 with a longer one in blue in Figure 3-18(b). No such sound was heard afterwards. Moreover, no oil was spotted to be permeated between two sides of the sample and the soft rubber after tests, indicating the lengthened path worked.

![Diagram](image_url)

**Figure 3-17** Most possible surface creepage path (not to scale)

![Photos and Illustration](image_url)

**Figure 3-18** (a) Photos and (b) illustration of sample protection (not to scale)
3.5 Measurement Units in PD Detection

PD measurement was conducted in this project with both methods detailed in Section 2.6, using products from Omicron®. The measurement instrument was an MPD 600 unit, the coupling device was a CPL 542 shown in Figure 3-19 with PD and voltage connections to the MPD 600, and the HFCT was an MCT 120 (operating frequency range of 80 kHz to 40 MHz [139]) shown in Figure 3-20 with a PD connection to the MPD 600. Unlike the coupling device (CPL 542), the HFCT (MCT 120) available in this project has only one BNC plug labelled PD; hence no voltage and therefore no phase information of partial discharges could be recorded if the MCT120 HFCT was the only measurement device in the circuit.

![Figure 3-19 Coupling device (CPL 542) connected with MPD 600.](image)

![Figure 3-20 HFCT (MCT 120) connected with MPD 600 [139].](image)

3.6 Superimposition of HVDC and AC

The High Voltage Lab in the University of Manchester possesses several Trek High-Voltage Power Amplifiers whose output is rated from 0 to ± 30 kV DC or 30 kV pk AC.
Therefore, one amplifier of this type with a waveform generator suffices when the maximum superimposition magnitude of DC and AC is no greater than 30 kV in absolute value [42][120][140]. However, separate sources of DC and AC are required when a much higher DC component is required in the superimposition, which is the case in this project.

There are three basic ways of superimposing two separate sources onto a test sample: a) two sources in series, b) two sources respectively applied to either side of the sample and c) two sources in parallel. The simplest sketch of each is shown in Figure 3-21, however, different types of extra electrical path components must be added in the sketches based on the power source types to ensure the circuit is able to work properly and safely.

![Figure 3-21 Sketches of three ways of superimposing two power sources to stress the sample.](image)

Regarding the first method in Figure 3-21(a), the connection is not possible because there is only one output cable from each HV source and in practice two sources cannot be connected in series. When the second method in Figure 3-21(b) is employed, PD measurement with a coupling capacitor will be no longer possible considering there is no grounding for the sample or the CPL (go back to Section 2.6.1 for arrangements using a coupling device). No phase information of PDs will thus be available. For example, DC and AC was applied this way in [39] and [55], but PD measurement was not even conducted in [39] and only PD magnitude was available using a HFCT in [55]. Hence, it was not selected for this project. The third method in Figure 3-21(c) successfully
resolved the PD measurement issue in terms of phase information and will be elaborated on in Section 3.7.

The last two methods in Figure 3-21 also apply when voltage sources of other types are superimposed; for instance, (b) was employed to superimpose DC and impulses to electrically stress a needle-plane sample which has been shown in Figure 2-19 [44] and (c) to superimpose AC and impulses [43]. Again, different electrical path components determined by source types are required to make circuits work. Examples are seen in the superimposition of AC and impulses in [43] and that of DC and AC in Section 3.7 in this project, though both employed the fundamental arrangement of Figure 3-21(c).

3.7 Experimental Arrangements

In this project, there were several versions of experimental arrangements due to different types of PD measurement and voltage superimposition being necessary to achieve the PD sensitivity required. Below is a summary of all the arrangements employed in this project.

3.7.1 List of Devices

Figure 3-22 shows the experimental arrangement with positive DC and AC sources in parallel including PD measurement with phase information. The HV zone is isolated in a cage to accommodate pieces of the equipment which generate high voltages to electrically stress the test sample and record PD signals. The safe zone is to control the HV power supplies and to monitor the voltage across the test sample and PD signals along with tree initiation and growth. The connections between the HV zone and LV controlling and monitoring zone are obtained by a BNC interface with spark gaps.

The key parameters and function for each device within the interlocked cage are as follows,
Figure 3-22 Electrical treeing with PD measurement under positive DC superimposed with AC stresses.

1) DC Source

Glassman High Voltage, ±100 kV DC power supply, maximum output current of 2.5 mA.

2) AC Source

Trek High-Voltage Power Amplifier 30/20A, maximum output voltage of ±30 kV DC or peak AC, maximum output current of ±20 mA DC or peak AC. Here it is used to amplify only the AC waveform which is generated in LabVIEW software and transferred to the amplifier via an NI box.

3) HV Diode

For the protection of the DC source from being loaded by the AC source. It is rated at 140 kV, 20 mA, 100 kΩ.

4) Current limiting resistor (R_lim)
A resistor rated at 20 MΩ to limit the current in the DC branch.

5) DC isolating capacitor (C_iso)

1.4 nF ± 5%, rated at 134 kV, to isolate the apparent DC current (D10: isolation of apparent DC current, Section 3.7.2) and therefore ensure the DC voltage component can be superimposed across the test sample.

6) PD blocking resistor (R_bl)

1 MΩ, to block reloading from the DC isolating capacitor (C_iso) and AC power supply when partial discharges occur; in operation it is two 500 kΩ resistors rated at 64 kV connected in series.

7) Coupling capacitor (Ck)

1 nF ± 5%, to recharge the test sample when PDs occur.

8) Coupling device

CPL 542 is the coupling device or the external measuring impedance to capture PD current signals.

9) HFCT

MCT 120 to capture PD signals in the ground cable of the test sample.

10) Omicron® MPD

The MPD 600 is the calculating and analysis unit, powered by a chargeable battery. There are two in Figure 3-22 labelled MPD 1.1 and MPD 2.1 which both go to the same MCU 502 outside the cage. The phase information recorded by MPD 2.1 (which is connected to the coupling device CPL 542) is shared with MPD 1.1 (which is connected...
to MCT 120). In this way PD signals detected by MCT 120 have both PD magnitude and phase information referenced to signals recorded by MPD 2.1.

It should be noted that PD measurement is achievable with only CPL 542 and MPD 2.1, which is exactly the arrangement in Figure 2-38 where CPL is connected in parallel with the test sample. However, it has its intrinsic shortcoming in PD sensitivity as mentioned in Section 2.6.1. In operation, it had a much taller background noise band than signals detected by MCT 120 in this project. That is why the HFCT was included in the circuit. Illustrations of the background noise bands are displayed in Figure 3-23, showing (b) has a taller noise band and therefore higher background noise than (a).

![Figure 3-23 Illustration of background noise bands with different heights displayed in MPD software](image)

After the circuit setup and before energising the cage and conducting PD measurement, the MPD systems should be calibrated. No voltage needs to be applied to the circuit when conducting calibration [100]. Figure 3-24 displays how to conduct PD calibration with an Omicron® calibrator CAL 542 for MPD 2.1 with the coupling device CPL 542 in (a) and for MPD 1.1 with the HFCT MCT 120 in (b). The calibrator should be as close to the test object \( C_a \) as possible, and the cables connected to the calibrator should be as short as possible.
11) High voltage potential divider

Ross Engineering, ratio 10,000:1; max operate at 300 kV DC or max AC; input 2.99 GΩ, 4.2 pF; output 626.48 kΩ, 40,660 pF.

12) CCD Camera

To capture images of tree initiation and growth. The camera is a Manta G-1236B with pixel dimension of 4112 x 3008 and the lens is a Optem FUSION component matrix (shown in Figure 3-25) with the magnification of 6x and a DoF (Depth of Focus) of 31 µm (D11: Choice of camera and lens matrix in tree initiation imaging in pure DC fields, Section 4.2.1).

The camera is enclosed in a securely grounded Faraday cage to protect it from any possible electromagnetic fields if the test sample fails when stressed under such high...
voltages as applied in this project. It happened that in such high DC fields the CCD camera began to lose connection at the moment of sample failure (though not every time) and once a camera became faulty due to sample failure in another DC breakdown testing circuit near it. Both are thought to be caused by the electromagnet field induced by sample failure.

13) Test cell

The schematic of the test cell to hold the test sample (one 22 x 22 x 22 mm³ cube for the sake of simplicity) and silicone oil is shown in Figure 3-26(a), with the dimensions detailed in Appendix II. To hold thin samples an LDPE clamp shown in Figure 3-26(b) is employed and, by changing the thickness \( t \) of the clamp, thin samples of different thickness can be placed in the same cell.

![Figure 3-26 Schematic of test cell and clamp to hold a thin sample.](image)

A spherical brass electrode illustrated in light yellow in Figure 3-27 is employed to connect the needle tail when the rest of the bare needle trunk is securely submerged
into the silicone oil to prevent possible corona discharges when HVDC is involved. The silicone oil also improves the teeing image quality.

![Spherical electrode to connect needle tail](image)

**Figure 3-27 Spherical electrode to connect needle tail**

Devices outside the interlocked cage are,

1) Omicron® MCU 502

The fibre optic bus controllers are powered via a USB plug, to act as the transmitter between the MPDs and the operating computer for PD measurements. As all the signals are transferred via optical fibre. There is no electrical connection to the MCU, making the LV zone being electrically isolated from the HV zone. In addition, the signal quality remains intact even with long distances and is immune to interference from electrical or magnetic fields.

2) NI USB box

This is a LabVIEW based DAQ device to do data exchange, for example sending ‘HV enable’ signals and voltage waveforms written in LabVIEW to the Trek amplifier and the Glassman DC supply and receiving voltage output from the HV potential divider.

3) Oscilloscope

To read the voltage output of the HV potential divider, which is also the voltage reading across the test sample; the same signals are also sent to the terminal pinout of one
analog input of the NI box and then analysed and displayed on the front panel of one of the LabVIEW files. These front panels are available in Appendix III.

### 3.7.2 Circuit Simulation by Pspice

Before supplying power to the experimental setup, a simulation is usually conducted to ensure the circuit works properly. Figure 3-28 shows the equivalent circuit of the HV zone (excluding HV divider) in the test arrangement in Figure 3-22 by the software OrCAD PSpice. The HV divider is a device to monitor voltages, effectively forming an open circuit for the HV zone when simulated and having insignificant influence on voltage reading. It is therefore omitted in this figure for the sake of simplicity, and the simulation including the divider can be found in Appendix IV. The power supplies are +20 kV DC and 5 kV pk AC, 50 Hz for instance; the typical capacitance of a needle-plane sample is reported to be 10 pF [59] and therefore employed in this simulation; the coupling device CPL is represented by its low-arm capacitance of 30 µF [141]. The probe in blue is to measure the voltage across the test sample. It should be noted that the resistor of 1 GΩ labelled $R_x$ is employed only as a solution to ‘floating nodes’ error from software’s perspective, otherwise the circuit diagram is not executable.

![Figure 3-28 Equivalent circuit of the test arrangement in Figure 3-22 by PSpice](image)
A floating node will be spotted by Pspice if there is no DC path from the node to ground, which is the case for Node a in Figure 3-28 and Node 2 in Figure 3-29. An artificial DC path should form through inductors, resistors and semiconductors while having negligible effect on the circuit calculation; a 1 GΩ resistor is recommended for the case in Figure 3-29 [142] and also works in the circuit in Figure 3-28.

To demonstrate the role of the DC isolating capacitor mentioned previously in Section 3.7.1, Figure 3-30(a) shows Figure 3-28 without the capacitor and Figure 3-30(b) shows the waveforms across the test sample in both circuits. The red waveform (without the capacitor) has little DC component compared with the blue one (with the capacitor) which shows the superimposed voltage including both DC and AC. Though it is not strictly correct to look at the circuit in Figure 3-30(a) using the superposition principle (in a linear system the net response, e.g., voltage and current in an electrical circuit, is the sum of the responses which would have been caused by each source independently) given that it is not a linear system in the presence of a diode, a general conclusion is still useful: when AC source is short circuited, there is only the blocking resistor (R_bl) from node p1 to earth and the apparent DC current flows mainly through R_bl due to the much higher impedance in its parallel branches (node p2 to earth and node p3 to earth); considering R_bl << R_lim, there is little DC voltage drop that can be measured by the red probe (Explained D10: isolation of apparent DC current).
Figure 3-30 (a) Circuit of Figure 3-28 but without isolating capacitor, (b) comparison of waveforms in both circuits (blue-Figure 3-28, red-(a) in this figure)

Sources of +20 kV DC together with 5 kV pk AC at 50 Hz gives rise to +22.85 kV DC with 2.85 kV pk AC across the sample in the simulation without the divider; the simulation including the divider in Appendix IV yields 21.97 kV DC with 2.84 kV pk AC with the maximum difference of ~0.88 kV shown in Figure 3-31, which is within the acceptable variation range because the simulation is only for qualitative analysis of the circuit rather than quantitative analysis.

Figure 3-31 Voltages across test sample in circuit in Figure 3-22: magenta-with divider, blue-without divider

The readings from on-site operation for the same source outputs are 22.01 kV DC with 3.05 kV pk AC, which also makes sense considering that parameters in Figure 3-28 are
ideal but products have their own tolerance and especially that the diode is only represented by a simplified valve without more details. The reduction of AC component across sample compared with the AC power supper (3.05 kV vs. 5 kV) is largely attributed to the voltage drop across the DC blocking capacitor.

The superimposed voltage across the test sample will be given in the format of ‘P DC ± AC pk’ or ‘N DC ± AC pk’ hereafter in this project. Figure 3-32 shows how to do the calculation: \( AC\ pk = \frac{\text{max} - \text{min}}{2} \), \( DC = \text{max} - \text{AC pk} \) (or \( DC = \text{min} + \text{AC pk} \)). Therefore, the voltages mentioned above can be logged for simplicity as ‘P22.80 ± 2.86’, ‘P21.97 ± 2.85’ and ‘P22.01 ± 3.05’. The AC frequency is 50 Hz when not stated.

That ‘P22.80 ± 2.86’ brought by sources of +20 kV DC together with 5 kV pk AC at 50 Hz has the DC component (P22.80) higher than DC source (+20 kV) is caused by the existence of the diode in the circuit. Figure 3-33 shows the waveform across the sample when DC source is set at 0 kV and AC source is set 12 kV pk in Figure 3-28, where the waveform gives rise to ‘P6.69 ± 6.98’. That is to say, in the circuit in Figure 3-28 the AC source only (i.e., with the DC source having no output at all) gives rise to both DC component together with AC component onto the test sample, which is a feature of the circuit employed in this project. Description like ‘P22.80 ± 2.86’ provides superimposed voltages across the sample and voltage sources will be like ‘SDC +20, SAC 5pk’ where needed. Hence, ‘SDC +20, SAC 5pk’ → ‘P22.80 ± 2.86’ fully describes the simulation in the circuit.
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Figure 3-33 Illustration of DC component brought by AC source only (‘SDC 0, SAC 12pk’ → ‘P6.72 ± 6.85’)

Figure 3-34 is a simplified diagram of Figure 3-22. Diagrams in Section 3.7.3 follow this drawing style.

Figure 3-34 Simplified diagram of HV zone in Figure 3-22

3.7.3 List of Experimental Arrangements

Figure 3-35 displays experimental diagrams under pure positive DC stresses with and without PD measurement. The calibration method was the same as in Figure 3-24(a) with the calibrator connected in parallel to the test sample. The CPL connected in series with the sample in Figure 3-35(b) yielded a lower background noise of 0.5 pC, compared with 2.5 pC when the CPL was connected in parallel with the sample in Figure 3-34.
However, this arrangement was not directly employed for tests under DC superimposed with AC stresses for a specific reason, which will be explained in Section 4.2.2 with the assistance of tree images (D12: Not CPL in series with test sample but HFCT was employed to record PDs in superimposition fields of HVDC and AC, Section 4.2.2).

Figure 3-35 Electrical treeing tests under positive DC stresses (a) without PD measurement and (b) with PD measurement

Figure 3-36 shows the experimental arrangement of treeing under negative DC superimposed with AC stresses by replacing the positive polarity module in the DC source with the negative one and the direction change of the diode, which yielded a background noise of ~4 pC.

Figure 3-36 Electrical treeing tests under negative DC stresses superimposed with AC ripples
Chapter 4  Treeing in Positive DC Fields and under Positive DC Superimposed with AC Ripples

The general procedure of investigating electrical treeing in pure DC fields and under DC superimposed with AC ripples was to 1) firstly determine the tree initiation voltage with an associated initiation time by Procedure 1 mentioned in Section 2.2.2 under pure DC stresses in both polarities (+V_{dc1} and -V_{dc1} hereafter) and then 2) superimpose AC ripples onto +V_{dc1} and -V_{dc1} respectively to observe the effect of AC ripples on tree initiation and growth, for example tree initiation time, tree shapes and PD behaviour. This chapter includes electrical treeing in positive DC fields and under positive DC superimposed with AC ripples.

4.1 Different PE Sheets vs. Test Results

The trial tests began with positive DC voltages without PD measurement. Table 4-1 displays the summary of tree initiation in the trial tests (batch TP, ‘Trial Positive’). The initiation time was defined as the time period from when the DC voltage reached the predetermined value (or target value hereafter) to when the first image including tree channels appeared. Images were set to be captured every single second; however, in rare cases some images were lost. This might be due to the massive data transfer between the computer and the equipment inside the HV zone (e.g, the camera via ethernet cable, voltage signal input and output via NI box, PD data via MCU 502) affecting, at a certain time point, the data save by the computer. For example, in TP2 the first image including tree channels was capture at 10:03:57 while the image prior to it, instead of 10:03:56, was 10:03:54, which showed no trees at all. Therefore, the initiation time for TP2 was recorded as 24-26 in column E in Table 4-1. The same occurred to TP3 which was recorded as 338-340 in column E. In both TP4 and TP7, the image one second prior to tree initiation was captured and showed no tree channels. Where there is a ‘N, >’ symbol in column E, there was no initiation in pure positive DC
fields after the corresponding time period of voltage application. In some of these cases (TP1, TP8 and TP9), an AC source at 150 Hz (in trial tests, a higher frequency AC was employed to accelerate tree initiation) was superimposed onto the existing DC. However, there was no tree initiation either in the superimposed fields after the corresponding voltage application during the period of ‘Test time (DC+AC)’ in column I. Column H was the DC component brought by the AC source when it had output, therefore, for example, TP1 was followed by ‘P(40+1.8) ± 3 @150 Hz’ for ~2 hours after stressed at +40 kV for ~3.5 hours without initiation. Initiation lengths in this project were measured vertically, as previously shown in Figure 2-13 by the solid line in white.

Table 4-1 Summary of tree initiation in positive DC fields in trial tests

<table>
<thead>
<tr>
<th>PE No.</th>
<th>Sample No.</th>
<th>DC ramp (kV/s)</th>
<th>Target DC (kV)</th>
<th>Initiation time by DC (s)</th>
<th>Initiation length (µm)</th>
<th>AC component (kV @ 150 Hz)</th>
<th>Extra DC (kV)</th>
<th>Test time (DC+AC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP1</td>
<td>0.2</td>
<td>+40</td>
<td>N, &gt; 3.5 hrs</td>
<td>-</td>
<td>3</td>
<td>+1.8</td>
<td>N, ~2 hrs</td>
<td></td>
</tr>
<tr>
<td>TP2</td>
<td>1</td>
<td>+40</td>
<td>24-26 *</td>
<td>544</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP3</td>
<td>0.5</td>
<td>+40</td>
<td>338-340 *</td>
<td>799</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP4</td>
<td>0.35</td>
<td>+40</td>
<td>367</td>
<td>607</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP5</td>
<td>0.35</td>
<td>+40</td>
<td>N, &gt; 2 hrs</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP6</td>
<td>1.8</td>
<td>+40</td>
<td>N, &gt; 2 hrs</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP7</td>
<td>2</td>
<td>+45</td>
<td>183</td>
<td>1121</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP8</td>
<td>0.45</td>
<td>+40</td>
<td>N, &gt; 1.5 hrs</td>
<td>-</td>
<td>5</td>
<td>+3.0</td>
<td>N, ~1 h</td>
<td></td>
</tr>
<tr>
<td>TP9</td>
<td>1</td>
<td>+40</td>
<td>N, &gt; 1.5 hrs</td>
<td>-</td>
<td>6.5</td>
<td>+4.0</td>
<td>N, ~2 hrs</td>
<td></td>
</tr>
<tr>
<td>TP10</td>
<td>1.5</td>
<td>+40</td>
<td>N, &gt; 3 hrs</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP11</td>
<td>1</td>
<td>+45</td>
<td>N, &gt; 2 hrs</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* DC ramp down rate was 1.0 kV/s in this whole project unless stated otherwise.

While more details in tree initiation in positive DC fields will be discussed in Section 4.2, this table raises a potential concern which did not emerge in AC fields. Though more tests are required before reaching a solid conclusion, there seemed to be different behaviour under DC stresses in samples fabricated from different commercial PE sheets. While +40 kV with appropriate ramp rates seemed to be a sensible voltage to initiate trees, in samples fabricated from PE sheet #2, neither +40 kV DC nor +40 kV DC superimposed with 150 Hz AC ripples was seen to have initiated trees in samples fabricated from PE sheet #3. Considering that the electric field distribution in DC fields is controlled by the conductivity of polymers rather than the permittivity in AC fields,
the possibility of the intrinsic conductivity differences among different PE sheets cannot be excluded, though no such different behaviour was seen in previous treeing tests in AC fields. Therefore, samples should be fabricated from the same PE sheet where possible. Samples described in the following sections were from PE sheet #4, stored in a desiccator with silica gel after fabrication to ensure ambient moisture is not a potential variable for treeing, and usually had the same sample age when tested.

4.2 Treeing in Positive DC Fields

There were two sample batches tested in positive DC tests: batch A without PD measurement using the experimental arrangement shown previously in Figure 3-35(a) and batch B with PD measurement using the experimental arrangement shown in Figure 3-35(b) yielding the background noise of 2.5 pC. The DC ramp rate was set at 1.0 kV/s unless stated otherwise. Images were captured every second. Table 4.2 shows the summary of tree initiation at various target DC voltages in batch A. Tests were terminated either shortly after tree initiation or after six hours if no trees were initiated. Two samples were stressed at +40 kV, however, neither was initiated after six-hour voltage application; only one of five samples was stressed at +43 kV; three out of six samples initiated trees at +45 kV. As can be concluded from the trial tests listed in Table 4.1, initiation times were all short in initiated cases with the maximum being slightly more than 6 minutes (24-26 s, 338-340 s, 367 s, 183 s), whereas up to ~ 3.5 hours could elapse without tree initiation. This also exhibited in Table 4.2: the maximum initiation time was only slightly more than 7 minutes and longer time period up to six hours could elapse without tree initiation. It is worth mentioning that though the DC ramp rate seemed to have an effect on the initiation time, no solid conclusion could be reached with limited tests shown here. The other phenomenon which appeared in trial tests in Table 4.1 and was confirmed by batch A in Table 4.2 was that the initiation included as long as > 600 µm tree channels (for images see Section 4.2.1) in the first image once
initiated. This is an order of magnitude longer than the tree initiation definition in AC fields, for which the literature invariably reports initial tree channels of ~10 µm in length.

Table 4-2 Summary of tests in batch A in positive DC fields [143]

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Target Voltage</th>
<th>Initiation time (s)</th>
<th>Initiation length (µm)</th>
<th>Time of failure (s)</th>
<th>Time test terminated (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-1</td>
<td>+40 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A1-2</td>
<td>+40 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A2-1</td>
<td>+43 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A2-2</td>
<td>+43 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A2-3</td>
<td>+43 kV</td>
<td>269</td>
<td>730</td>
<td>-</td>
<td>418</td>
</tr>
<tr>
<td>A2-4</td>
<td>+43 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A2-5</td>
<td>+43 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A3-1</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A3-2</td>
<td>+45 kV</td>
<td>339</td>
<td>610</td>
<td>-</td>
<td>701</td>
</tr>
<tr>
<td>A3-3 *</td>
<td>+45 kV</td>
<td>263</td>
<td>≥860 **</td>
<td>-</td>
<td>374</td>
</tr>
<tr>
<td>A3-4</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A3-5</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>A3-6</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
</tbody>
</table>

* A3-3 was ramped up at 0.05 kV/s.
** Initiation tree channels reached beyond the field of view (FoV) of CCD camera hereafter.

Considering that three out of six samples (50%) were initiated at +45 kV in batch A, +45 kV could be regarded as the initiation voltage under positive DC stress and was selected for the following tests in batch B with PD measurement. Tests in batch B were terminated either when the test sample failed or after six-hour voltage application after initiation, with B2 as the exception where the test circuit was switched off shortly after initiation. Table 4-3 shows the summary of tree initiation at +45 kV in batch B.

Table 4-3 Summary of tests in batch A at +45 kV by 1 kV/s ramp rate [143]

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Target Voltage</th>
<th>Initiation time (s)</th>
<th>Initiation length (µm)</th>
<th>Time of failure (s)</th>
<th>Time test terminated (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>+45 kV</td>
<td>5</td>
<td>700</td>
<td>15,120</td>
<td>15,120</td>
</tr>
<tr>
<td>B2</td>
<td>+45 kV</td>
<td>1636</td>
<td>1050</td>
<td>-</td>
<td>1,658</td>
</tr>
<tr>
<td>B3</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>B4</td>
<td>+45 kV</td>
<td>-2 *</td>
<td>630</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>B5</td>
<td>+45 kV</td>
<td>14</td>
<td>≥930</td>
<td>-</td>
<td>21,600</td>
</tr>
<tr>
<td>B6</td>
<td>+45 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21,600</td>
</tr>
</tbody>
</table>

* Initiation occurred at the moment when DC reached +43 kV.
Four out of six samples in batch B were initiated. However, it should be noted that in sample B4 initiation occurred at the moment when DC reached +43 kV while it still kept going up to the target value +45 kV. The short initiation time in initiated cases contrasted with up to six hours in cases without initiation and very long channels once initiated were also seen in samples in batch B.

4.2.1 Tree Initiation Images in Positive DC Fields

Figure 4-1 displays the images of initiation tree channels, where the red arrows in sample A3-3 and B5 indicate initiation channels reached beyond the field of view (FoV) of the CCD camera. The pixel dimension of the images is 4112 x 3008 (determined by the size of the CMOS sensor), and the pixel size is in the range between ~0.546 and ~0.549 with the 6x lens. Therefore, the images can only include an area of ~2250 x ~1650 µm, which is smaller than the area of interest in these treeing images. This is a compromised imaging solution in DC fields.

Figure 4-1 Tree initiation images in (a-d) batch A and (e-h) batch B [143]

Figure 4-2(b) shows the contrast and sharpness enhanced image of sample B4 after six-hour voltage application with a ‘full’ FoV which is cropped to share the scale bar in Figure
4-2(a) for easy comparison with tree initiation image. With a bigger FoV comes a smaller pixel size, which as a result captures less detail in images. The camera (Manta 504B with pixel dimension of 2452 x 2056) and lens in Figure 4-2(b) is the standard setting for AC tree imaging, but it fails to capture proper real-time images of DC tree channels which are thinner in diameter and therefore lighter in colour. Hence, it makes sense to sacrifice the FoV to get a higher magnification under this circumstance. There is a single 8x lens by LINOS® but it has a limited DoF. Therefore, the Manta G-1236B CCD camera and the 6x lens matrix with a 31 µm DoF mentioned in Section 3.7.1 were selected for DC tree initiation imaging in this project (*Explained D11: Choice of camera and lens matrix in tree initiation imaging in pure DC fields*).

![Figure 4-2](image)

*Figure 4-2*  B4 Images (a) of initiation with a limited FoV and (b) after six-hour voltage application with a bigger FoV, scale bar applies to both.

Figure 4-3 shows initiation images of TP4 and TP7 and images of TP2 and TP3 with at most two-second growth listed in trial tests in Table 4-1. The fogginess in images, as well as that in Figure 4-1, were due to contamination in the silicone oil such as fibres from blue rolls or oil absorbent pads when handling samples and the sample holder which was submerged in the oil tank during test. It was not easy to eliminate the effect of the contamination though the oil was filtered more regularly and frequently than for tests in AC fields. This is because such high DC application usually leads to oil vibration around the sample especially during DC ramp process, which as a result drives any sediment to move and disperse. The extreme example is shown in Figure 4-4, where ripples in the oil can be seen during DC ramp at 2 kV/s. The pictures are screen captures from a cell phone video when conducting DC breakdown tests in silicone elastomer compound sheets.
Chapter 4: Treeing in Positive DC Fields and under Positive DC Superimposed with AC Ripples

(results from these tests do not form part of this thesis). No accurate timestamps are available for the pictures as these were breakdown tests rather than treeing tests. However, these images in Figure 4-4(b) were taken when the applied voltage reached approximately 45-55 kV. Another consequence of oil vibration is to change the optical path from CCD camera to the focus plane to result in a blurry initiation image in some cases.

![Figure 4-3 Images in trial tests in Table 4-1: at most two seconds after initiation in (a) TP2 and (b) TP3; initiation of (c) TP4 and (d) TP7; scale bar applies to all.](image)

![Figure 4-4 Ripples in oil during DC voltage ramp up in breakdown tests, the dashed red rhombus outlines the test sheet; results from these tests do not form part of the thesis.](image)

From Figure 4-1 and Figure 4-3, initiation tree channels in positive DC fields were seen to have a very long and circuitous branch structure, which is very different from the tree structure initiated by a pure AC voltage but has similarity with trees initiated by a single lighting pulse shown in Figure 2-13. Furthermore, it is worth mentioning that the initiation images are only as accurate as the CCD camera with lens can capture, since it seems that channels could exist out of DoF plane and might have longer propagation...
than they can display in the image, such as in the channels circled in sample TP2 in Figure 4-3(a).

### 4.2.2 Tree Growth in Positive DC Fields

Unlike the gradual tree growth in AC fields, tree channels barely developed further under positive DC stresses after initiation (which included very long initiation lengths), as shown in Figure 4-5. No further growth was seen when comparing the initiation image of B1 in Figure 4-1(e) with the image after 252-minute voltage application at +45 kV in the same sample in Figure 4-5(a), which was also one second prior to sample failure. However, further channel development circled in red was observed almost simultaneously when sample failed, as shown in Figure 4-5(b). Due to the difficulty in locating the needle tip in Figure 4-5(b), the breakdown channel length is not readily measurable; however, it is certainly less than 1000 µm. The same phenomenon of no further growth was also seen in both B4 during six-hour voltage application by comparing Figure 4-1(g) with Figure 4-5(c) and B2 during ten-minute voltage application. There is a little growth occurring in B5 circled in Figure 4-5(d) where the red arrow indicates initiation (not the growth) channels beyond the FoV; however, it was almost negligible compared with tree growth in AC fields especially in terms of 2D ‘damage’ area by treeing. Based on this information, images of TP2 and TP3 with at most two-second growth in Figure 4-3(a) and (b) might well be considered as initiation images.

![Figure 4-5 Images of tree growth: (a) 1 second before and (b) the right moment of sample failure in B1 and simultaneous further channel propagation circle in red; last image of (c) B4 and (d) B5 after six-hour voltage application and further channel growth circled in red, the red arrow indicating the initiation channels beyond the FoV [143]](image)
The failed channels in Figure 4-5(b) were catastrophic compared with failed channels in LDPE in AC fields as shown in Figure 4-6. Moreover, Omicron® MPD and MI software shut down after sample failure (probably due to the change in the electromagnetic field induced by sample failure) and software restart was required, which never occurred in pure AC fields. It has been mentioned in Section 2.6.1 that the arrangement of the CPL in series with the test sample (Figure 2-39 and Figure 3-35b) has a much higher probability of damaging the CPL and MPD 600 system when the sample fails, as the CPL will be exposed to the full test voltage. After comparing the arrangement of the CPL in parallel with the test sample (illustrated in Figure 2-38 which yields a lower sensitivity compared with the CPL in series with test sample) and the usage of HFCT (shown in Figure 3-34) under positive DC superimposed with AC voltages, a higher sensitivity was obtained. Hence HFCT was employed in the subsequent tests reported in the following text (Explained D12: Not CPL in series with test sample but HFCT was employed to record PDs in superimposition fields of HVDC and AC).

Figure 4-6 Failed channels in LDPE at (a) 12 kV pk and (b) 15 kV pk, AC only [42]

Figure 4-7 illustrates sample failure channels in B1 in Figure 4-5(b), which occurred through the side surface of the sample via the LDPE/oil surface rather than that between LDPE and ground electrode shown in Figure 4-6. Though the LDPE sample is fairly thin (3.18 mm), channel failure through the side surface never occurred in LDPE treeing samples with the identical geometry in AC fields.
4.2.3 PD Signals in Positive DC fields

In contrast to experience in AC fields, PD signals recorded under positive DC fields showed no difference in either PD magnitude or PD occurrence before and after tree initiation. B2 is given as an example in Figure 4-8: data being calculated every half second.

However, PD signals usually accompany tree growth right after initiation in AC fields in LDPE. Figure 4-9 takes an air gap free sample stressed at 8.4 kV pk AC (sample A4 in [53] with the smallest pixel size and best image quality) as an example, and shows the image of tree initiation (~15 µm in length) and that after 20 seconds. It also displays 20-second PRPD patterns before and after initiation replayed with the same sensitivity of PD measurement as B2 in Figure 4-8 (0.5 pC). Considerable PD signals with the magnitude between 0.5 pC and ~2.0 pC were detected right after initiation while there were few PDs 20 s prior to initiation.
Moreover, PD signals could not predict sample failure in B1 in the way they did in AC fields by having PD events with higher magnitudes prior to failure (shown previously in Figure 2-53), as neither PD events of higher magnitudes nor any increase in the rate of PD occurrence was seen to lead up to failure within the last 20 minutes, as is shown in Figure 4-10.

PD occurrence was also far less frequent in DC fields than in AC fields. There was, on average, less than one PD event every 0.02 s (one cycle if 50 Hz AC) in B2. The rate of PD was even lower in B1, showing less than ten PD events in every minute.
4.3 Treeing under Positive DC Superimposed with AC Ripples

It has been shown in the simulation result in Figure 3-33 and from the in-situ voltage reading in the trial tests in Table 4-1 that the AC source brought a DC component to the test sample. Hence, the AC source was electrically enabled first and then DC source ramping up at 1.0 kV/s followed for easy operation. The AC source was increased in steps of 1.0 kV pk and each step lasted for 30 seconds before the next increase. ‘SDC +42, SAC 8.2pk’ $\rightarrow$ ‘P45 $\pm$ 5’ was selected as the superimposition after preliminary tests where ‘P40 $\pm$ 5’ and ‘P45 $\pm$ 3’ across the sample showed no tree initiation with six-hour voltage application.

4.3.1 Initiation/Simultaneous Sample Failure at ‘P45 $\pm$ 5’

Eight samples (P1-P8 in [143], here labelled as PS1-PS8 to distinguish from voltage superimposition abbreviation) were stressed at ‘P45 $\pm$ 5’. Four samples (PS4, PS5, PS6 and PS8) did not initiate after six hours in the superimposition fields, whereas tree initiation and subsequent sample failure occurred almost simultaneously in the other four samples (PS1, PS2, PS3 and PS7), as shown in Figure 4-11.
Sample PS2 shown in Figure 4-11(c), as B1 under pure +45 kV, failed through the side surface of the sample via the LDPE/oil surface, while the other three needed to be placed in front of another lens with a larger FoV after tests to include their whole breakdown channels. Though images were captured every single second, tree initiation and sample failure were not in separate pictures in sample PS1, PS2 and PS3. In sample PS7, fortuitously, the image one second prior to the breakdown event was captured to include initiation channels, as shown in Figure 4-11(g). It indicated that at ‘P45 ± 5’, sample failure could follow initiation within less than one second. Moreover, from the breakdown channels and the surviving branches in Figure 4-11 trees formed at ‘P45 ± 5’ seemed to be longer and more circuitous than those formed at pure +45 kV.

4.3.2 PDs During DC Ramp Up at ‘P45 ± 5’

Though PDs could not act as an indicator of treeing in pure DC fields, they did provide distinguishing information between the initiated/failed samples and others at ‘P45 ± 5’. A summary of initiation/simultaneous sample failure and PD signals (background noise level of 2.5 pC) measured during the 42-second DC ramp up is given in Table 4-4, except that data for PS3 included only 32 seconds and was extracted from the ramp up as the period was obscured by external interference. The initiation/BD time in the table was from when the voltage reached its full superimposition (i.e., ‘P45 ± 5’) to when initiated channels, if existing, or failed channels occurred. It can be seen from the table that during the DC ramp up both the PD number and PD magnitudes tended to be larger in
samples which went on to initiate trees than those which did not. In terms of net PD energy, the initiated/failed samples, including PS3 with incomplete data set, all had PD energy larger than 19 µJ with an average of > 47 µJ while those without trees had a net energy <10 µJ with an average of 4.87 µJ.

Table 4-4 Summary of tests at ‘P45 ± 5’ and PD information for the DC ramp up period [143]

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Initiation time (s)</th>
<th>Breakdown channel length (µm)</th>
<th>PD max magn. (pC)</th>
<th>PD number</th>
<th>Energy (10⁻⁶ J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>13</td>
<td>2260</td>
<td>8.22</td>
<td>107</td>
<td>19.88</td>
</tr>
<tr>
<td>PS2</td>
<td>8</td>
<td>1160</td>
<td>32.2</td>
<td>187</td>
<td>61.58</td>
</tr>
<tr>
<td>PS3</td>
<td>41</td>
<td>2300</td>
<td>30.8</td>
<td>54</td>
<td>&gt;30.44*</td>
</tr>
<tr>
<td>PS4</td>
<td>-</td>
<td>-</td>
<td>10.3</td>
<td>98</td>
<td>9.89</td>
</tr>
<tr>
<td>PS5</td>
<td>-</td>
<td>-</td>
<td>9.32</td>
<td>31</td>
<td>5.13</td>
</tr>
<tr>
<td>PS6</td>
<td>-</td>
<td>-</td>
<td>7.95</td>
<td>17</td>
<td>2.88</td>
</tr>
<tr>
<td>PS7</td>
<td>0 **</td>
<td>1810</td>
<td>1528</td>
<td>20</td>
<td>76.28</td>
</tr>
<tr>
<td>PS8</td>
<td>-</td>
<td>-</td>
<td>6.90</td>
<td>11</td>
<td>1.59</td>
</tr>
</tbody>
</table>

* Data for sample PS3 is incomplete, as detailed in the text.
** Initiation/failure occurred when DC component reached +45 kV.

Figure 4-12 displays the PRPD patterns in all the samples during DC ramp up (note that PS3 only includes 32-second PD data). Samples which would develop to include trees after DC ramp up had either more PD events between 0° and 180° (i.e., in positive AC half cycles) than between 180° and 360° (i.e., in negative AC half cycles) or, as the case in PS7, one PD event of a very high magnitude, i.e. 1.53 nC circled in Figure 4-12(g). Moreover, these PD events appeared close to the phase 90° in the waveform, which was the peak value in each cycle. On the contrary, PD events occurring during DC ramp up in samples without initiation channels following tended to be fewer in number, smaller in magnitudes and distributed evenly in both half cycles.
4.4 Discussion of Results with Positive DC Involved

Tree initiation and growth under positive DC stresses in this work exhibited distinct features from under AC stresses. A much higher voltage was required to initiate a tree in polymers in positive DC fields than in AC fields, which has been well explained in Section 2.3.2 by electric field alleviation resulted from space charge build-up around the needle tip. Initiation in positive DC fields was also found very sensitive to the voltage magnitude, with +45 kV resulting in 3 out of 6 samples (50% probability) to initiate trees and a decrease by 2 kV in magnitudes leading to 1 out of 5 (20% probability).

In terms of the initiation tree length, AC fields usually gave rise to ~10-20 µm long channels vertically, while positive DC voltages, at the very moment of initiation, resulted in channels with more than one order of magnitude longer in length (> 600 µm) than those in AC fields. These initiation channels were branch-like in structure and usually had sub-branches developing from the main skeleton channels. Tree initiation in DC fields is considered as local intrinsic breakdown [24] with energy release leading to
electro mechanical cracking in polymers in the form of tree-like channels. It has been well reviewed in Section 2.3 that charge injection and space charge accumulation is expected in polymers when HVDC is applied to the needle tip. Therefore, the initiation tree length under positive DC stresses can be attributed to the energy released into the polymer when energy stored in the space charge/free volume system within the polymer exceeds the local intrinsic breakdown strength. Since a much higher positive DC voltage, i.e., up to +45 kV, is required to initiate a tree, the much longer initiation tree length to alleviate the initiating stress (voltage) around the needle tip appears not surprising. The addition of AC ripples of 5 kV pk to the positive DC initiation voltage (+45 kV) in the ‘P45 ± 5’ cases might be seen as a trigger mechanism which allows or facilitates the stored energy to be released in the form of tree-like channels. With the maximum voltage as +50 kV periodically, which is higher than the pure DC case of +45 kV, longer initiation/failure channels are expected. There was no process of treeing ageing or gradual degradation in this case.

Under AC stresses continuous and repetitive partial discharges are accommodated in the hollow channels after tree initiation, which in turn erode channel wall and facilitates tree growth gradually. It makes PD analysis a powerful tool for monitoring electrical ageing in AC fields. However, it seems difficult to employ PD signals as an indicator of degradation in positive DC fields. No changes in either PD magnitude or PD occurrence rate were found between before and after tree initiation, or in a period before sample failure. Furthermore, little further growth was seen in positive DC fields with such long initiation channels (>600 μm). Treeing is not a contributary factor to failure in positive DC fields as it is in AC fields. It would not be right to suggest in pure DC fields that trees gradually grow and lead to failure. Even if tree-like channels are seen, the failure seems to always be a short time catastrophic event.

Unlike in pure positive DC fields, useful information could be extracted in two ways from PD signals during the DC ramp up in the superimposition fields at ‘P45 ± 5’. One was that more PD events occurred in the positive AC half cycles than the negative AC ones in
samples which would go on to develop a tree (‘containing trees’ hereafter) while in samples which would not, PD events tended to be fewer in number and distributed relatively evenly in both cycles. This is a key difference, also easy to notice (see Figure 4-12), between samples containing trees and without. The other was that the energy released by PDs was much larger in samples containing trees than samples without (see Table 4-4).

Tests at ‘P45 ± 5’ resulting in much shorter breakdown times (0-41 s in Table 4-4 vs. only one sample failure in B1 after 15120 seconds stressed at +45 kV in Table 4-3) and longer breakdown tree channels (≥1160 μm in Table 4-4 vs. shorter than 1000 μm in B1 in Figure 4-5) indicates that the power quality is critical in HVDC projects and AC ripple superimposition onto DC voltages may considerably compromise the performance and reliability of the insulation systems.

It has been known from Section 2.2.4 that when the DC component in a DC-AC composition field was relatively low compared to pure DC initiation voltages, tree initiation was dominated by the AC component which was also very close to the initiation voltage in pure AC fields [39]. This work added more information to the topic (i.e., treeing in DC-AC superimposition fields) and showed that at the positive DC initiation voltage, an extra AC ripple as low as 5 kV pk could cause catastrophic failure to the insulation. Therefore, the power quality (especially the presence of AC harmonics caused by power converters as mentioned previously in Section 1.1.2) in positive HVDC networks should be monitored closely, especially in a long term when the insulation naturally ages over time and results in weaker electrical properties such as a lower positive DC initiation voltage.

### 4.5 Conclusions with Positive DC Stresses Involved in Treeing

This chapter presented and discussed electrical treeing LDPE in pure positive DC fields and under positive DC superimposed with AC ripples, which yields conclusions as follows,
1) In terms of electrical tree initiation, trees initiated in pure positive DC fields were much longer in length and tended to be less bushy but more branchy in structure than in AC fields. This is due to the much higher stresses involved in positive DC fields, which in turn leads to higher levels of energy being stored in polymers before the formation of initiation channels. This can be compared to crack growth in glass, which grows rapidly to reduce high stresses.

2) For the needle-plane geometry in LDPE samples in this work, the tree initiation voltage in positive DC fields was close to the short-term local breakdown voltage. Hence, it was initiation times that dominated the life expectancy of the insulation rather than treeing degradation or tree growth as in AC fields. In fact, it would be misleading to describe the failure process as one of tree growth.

3) PD interpretation was difficult in pure positive DC fields. However, PD measurement was a useful tool when AC ripples were superimposed with positive DC. Key differences in terms of PD event distribution and PD energy were observed in the two half cycles of the AC component, and this may be used as an indicator of treeing activity in asset management. An intrinsic ripple in DC systems may be employed for this or, alternatively, an artificial AC ripple may be imposed to facilitate PD interpretation in the presence of electrical trees in DC networks, though it should be noted that the artificial AC ripple may also pose an additional threat as it may trigger treeing in an otherwise healthy insulation system.
Chapter 5  
Treeing in Negative DC Fields and under Negative DC Superimposed with AC Ripples

This chapter includes the counterpart of Chapter 4, i.e., electrical treeing in negative DC fields and under negative DC superimposed with AC ripples using the experimental arrangement shown in Figure 3-36. However, a different voltage application procedure was employed after preliminary tests. The negative DC source (Glassman), instead of the AC source (Trek), was electrically enabled first and increased to a target value at 1.0 kV/s. If there was no tree initiation after a certain period of time, the AC source would be enabled to provide AC component onto the test sample, and the sample would be considered one stressed at the superimposed voltages; if there was tree initiation, the sample would be considered one stressed at a pure negative DC voltage. This voltage application was employed to ensure that almost each test sample ended up having a tree inside, ‘wasting’ fewest samples from PE sheet #4, the same PE sheet as in Chapter 4 under positive DC fields, considering that there might be intrinsic conductivity differences among different PE sheets as mentioned previously in Section 4.2. More importantly, space charge (electrons mainly) would have more time to build up distribution before AC ripples were to be superimposed. It should be noted that samples in Chapter 4 were fabricated from three to four months earlier than the planned test dates and therefore three to four months old when tested, whereas those in this chapter were fabricated along positive DC tests but eight to nine months old when tested due to the delay in laboratory work by COVID-19 lockdown.

5.1 Preliminary Tests to Decide on Voltage Superimposition

Table 2-1 summaries the trial tests of tree initiation by negative DC voltages (batch TN, ‘Trial Negative’). Though the tree initiation voltage in negative DC fields is expected to be higher than that in positive fields, which has been reviewed in Section 2.2.2, ‘N45 ± 5’ was still employed to facilitate the direct comparison with ‘P45 ± 5’. There was no tree
initiation after ~2 hours in this case (sample TN1). The absolute value of DC component was then increased by 5 kV each step at 1.0 kV/s till 60 kV to get ‘N60 ± 5’ and in each step the sample was stressed with the superimposed voltages for 1 hour. This resulted in no tree initiation either (sample TN2). Then the increase in AC component followed at 1 kV pk each step when DC was applied first this time. There was no initiation after 0.5-hour voltage application at both ‘N60 ± 5’ and ‘N60 ± 6’ until ‘N60 ± 7’ was superimposed onto the sample (sample TN3). Initial trees which were like ones in AC fields appeared after ~2 minutes.

The same voltage ramp-up sequence as in sample TN3 had been planned for TN4. Given than ‘N60 ± 7’ across the test sample was brought by ‘SDC -56, SAC 11.4pk’, the DC source was enabled first and set at -56 kV. However, initiation channels appeared when DC reached -45 kV while it kept going up to -56 kV, and the sample failed 67 seconds after initiation, i.e., 56 seconds after DC reached -56 kV. Sample failure in this electric field (and the electromagnetic field it induced) resulted in not only Omicron® MPD and MI software shutting down itself, but the MPD 600 units had to be restarted physically before the software could be restarted properly. Hence sample failure in such high negative DC fields should be avoided when possible.

Based on the preliminary tests above and the short initiation time featured in sample TN4 and samples in positive DC fields in Chapter 4, the voltage ramp-up procedure illustrated in Figure 5-1 was decided on. The pure negative DC voltage was first applied

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Source sequence</th>
<th>Voltage across sample (kV)</th>
<th>~Test time (h)</th>
<th>Initiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN1</td>
<td>SAC †, SDC †, SDC †, SAC †</td>
<td>N45 ± 5</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>TN2</td>
<td>SAC †, SDC †, SDC †, SAC †</td>
<td>N45 ± 5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N50 ± 5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N55 ± 5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N60 ± 5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>TN3</td>
<td>SDC †, SAC †, SDC †, SAC †</td>
<td>N60 ± 5</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N60 ± 6</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N60 ± 7</td>
<td>y, after ~2 min</td>
<td>-</td>
</tr>
<tr>
<td>TN4</td>
<td>Planned as TN3</td>
<td>N56</td>
<td>2.5</td>
<td>y, at -45 kV</td>
</tr>
</tbody>
</table>

*SAC refers to the AC voltage source (Trek amplifier), SDC refers to the DC voltage source (Glassman DC supply).
to -45 kV at 1.0 kV/s and held for 5 minutes (Phase I); if there was no initiation the DC source was increased to -56 kV and held for another 5 minutes (Phase II); if there was still no initiation, the AC source would be enabled and increase at 1.0 kV pk each step and in each step the voltage held for 1 minute till its output was 11.0 kV, which took 11 minutes in total (Phase III); another 0.4 kV increase from the AC source was required to obtain ‘N60 ± 7’ across the sample (Phase IV). -45 kV, -56 kV and ‘N60 ± 7’ was considered as target values, the initiation time was from when it reached the corresponding target value to when the first image appeared including initiation channels. Images, as in positive DC fields, were captured every single second.

![Figure 5-1 Voltage superimposition sequence to obtain ‘N60 ± 7’](image)

5.2 Treeing in Negative DC Fields

There were samples initiated in both Phase I at -45 kV and Phase II at voltages with higher absolute values after the survival from Phase I. The former was labelled group C and the latter group D.

5.2.1 Initiation and Growth in Negative DC Fields

Table 5-2 summarises tree initiation and growth in negative DC fields, where the growth time was from initiation to when the voltage began to ramp down at 1.0 kV/s. Tree lengths were closely monitored to avoid any possible sample failure which could cause potential damage to the MPD units. That was why the growth time was very limited in group D. Sample D3-D5 were initiated during the ramp up from -45 kV while the voltage
kept rising to -56 kV, however, the absolute values of initiation voltages were all larger than 53 kV.

Table 5-2 Summary of tree initiation and growth in negative DC fields

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Target voltage (kV)</th>
<th>Initiation time (s)</th>
<th>Initiation length (µm)</th>
<th>Growth time (s)</th>
<th>Final length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-45</td>
<td>2</td>
<td>28</td>
<td>931</td>
<td>904</td>
</tr>
<tr>
<td>C2</td>
<td>-45</td>
<td>40</td>
<td>20</td>
<td>1635</td>
<td>998</td>
</tr>
<tr>
<td>C3</td>
<td>-45</td>
<td>0</td>
<td>54</td>
<td>7331</td>
<td>630</td>
</tr>
<tr>
<td>D1</td>
<td>-56</td>
<td>2</td>
<td>428</td>
<td>22</td>
<td>1082</td>
</tr>
<tr>
<td>D2</td>
<td>-56</td>
<td>1</td>
<td>273</td>
<td>16</td>
<td>817</td>
</tr>
<tr>
<td>D3</td>
<td>-56</td>
<td>-1, at -55kV</td>
<td>297</td>
<td>55</td>
<td>986</td>
</tr>
<tr>
<td>D4</td>
<td>-56</td>
<td>-3, at -53 kV</td>
<td>32</td>
<td>42</td>
<td>≥1323</td>
</tr>
<tr>
<td>D5</td>
<td>-56</td>
<td>-1, at -55 kV</td>
<td>50</td>
<td>66</td>
<td>≥1387</td>
</tr>
</tbody>
</table>

Much shorter initiation times were seen from the table in negative DC fields compared with hundreds of seconds in positive DC fields. The initiation lengths (20-430 µm) were also shorter than those in positive fields (> 600 µm) in Table 4-2. Initiation length at -45 kV was shorter than in group D; tree lengths in group C never reached beyond 1000 µm though with longer growth times and initial lengths of longer than 250 µm only occurred in group D which was set to stress at the higher voltage of -56 kV.

Figure 5-2 shows the initiation images of group C, where (b-1), (b-2), (c-2) and (c-3) of one second before or after the initiation are displayed for easy comparison with the initiation in C2 and C3. Therefore, a deviation, for example ± 2~3 µm, should be sensibly included in the measurement of initiation lengths. A single branch structure was seen in the initiation of the three samples, and lengths of C1 and C2 had pronounced similarity with initiation in AC fields.

Figure 5-2 Images of (a) C1 at initiation; C2 at (b-1) 1 s prior to initiation, (b-2) initiation and (b-3) initiation with the initial channel highlighted in red; C3 at (c-1) initiation, (c-2) initiation with the initial channel highlighted in red and (c-3) 1 s after initiation; scale bar in (a) applies in all.
Figure 5-3 shows the initiation in group D, where the initiation in D5 was determined by two more images of one second before and after initiation. Longer channels usually with thinner sub-branches from the main skeleton channels were seen in sample D1-D3 whereas D4 and D5 exhibited similarity with the initiation at -45 kV in C1 and C2, which was the short single channel structure.

![Figure 5-3](image)

**Figure 5-3** Images of (a) D1, (b) D2 and (c) D3 at initiation sharing 100 µm scale bar in (a); (d) D4 at initiation, D5 at (e-1) 1 second prior to initiation, (e-2) initiation with a red line to the right of the initial channel and (e-3) 1 second after initiation sharing 100 µm scale bar in (d).

Figure 5-4 shows the final channels in each sample before the DC source began to decrease. Much more sub-branches in a broader tree structure grown for a much shorter time period were seen in sample group D which initiated at higher voltages than those in group C which initiated at -45 kV. Note again that tree channels could grew beyond the DoF plane, for example, the circled channels in D2 and D3, hence channel lengths listed in Table 5-2 were ones measured from 2D images shown in Figure 5-4.
Figure 5-4 Tree growth in negative DC fields: (a), (b), (c) and (d) share scale bar in (a); (e) and (f) share scale bar in (e); (g) and (h) share scale bar in (g), red arrows indicate channels grew beyond FoV.
Figure 5-5 is the tree length (vertical measurement) plot over time in group C and group D, where t = 0 in (a) was when the DC source began to rise from 0 to -45 kV while that in (b) was when it ramped up from -45 kV to -56 kV. Unlike in positive DC fields where little growth occurred within six hours of voltage application with longer initiation channels in the first place, considerable tree channel propagation was seen within a very short time period right after initiation in negative DC fields. The propagation exhibited a step-like feature as a considerable length could occur within one second.

Group C at -45 kV was stressed with longer times whereas trees stopped growing before t = 400 s in Figure 5-5. Therefore, the ‘Final length (µm)’ column in Table 5-2 was also the length when trees stopped growing for group C. Figure 5-6 plots the stopping length against the initiation, which yielded a linear trend (though only three dots) of the longer initiation length having a shorter propagating distance in total.
5.2.2 PD Signals in Group C

It has been known from the onsite experience that PDs could be recorded during DC ramp up before becoming fewer till disappearance (when the circuit had sufficiently low background noise). Therefore, a data filter of 5 pC was selected to exclude PDs which might have been brought about by the DC ramp up. Figure 5-7 plots the tree length (in blue) and the maximum PD magnitude (in orange) against time in seconds in group C, where t=0 was when the DC source began to ramp from 0 to -45 kV and dots with the magnitude being zero indicated no PDs higher than 5 pC occurring within that second.

The PD occurrence rate was usually only one event in one second if there were any. PD began to appear after initiation in C1 and C2 which had initiation length shorter than 30 µm but before initiation in C3 whose initiation length was longer than 50 µm. PD
magnitudes were higher accompanying the fast channel propagation in the early growth stage and then dropped when the channel length propagation slowed down or stopped. They decreased to lower than 30 pC ~60 seconds after tree channels reached ~900 µm in C1, and in C2 and C3 PDs to lower than 60 pC ~300 seconds after the voltage application when tree channels were ~770 µm long in C2 and ~560 µm long in C3.

### 5.2.3 PD Magnitude Reliability

In this project, PD events of very high magnitudes (higher than 500 pC and up to 1-2 nC as recorded) occurred in negative DC fields after the DC source ramped up from -45 kV to -60 kV. Since it was usually only one PD event of a very high magnitude that led to PD overdriven in the MPD unit, in theory the magnitude recorded might not be accurate; only the occurrence of very high magnitude PD events can be considered certain. Therefore, such PD events will be described as PD overdriven or PDs higher than 500 pC hereafter. In retrospect, the better option would have been to set the CPL together with MPD 2.1 at a very high threshold (for example at 500 pC or even at 1.0 nC) to exclude PD events with much smaller magnitudes, then the PD overdrive issue at higher negative DC might have been resolved in MPD 2.1 (while MPD 1.1 could still record PD events with smaller magnitudes) and the PD signals which would be recorded in MPD 2.1 with high magnitudes might only be linked to the DC voltage.

### 5.2.4 PD Signals in Group D

Samples in group D, which survived from the five minutes at -45 kV, no PDs higher than 5 pC were seen not only during the ramp up from 0 to -45 kV, as was the case in group C, but also during the five minutes at -45 kV, i.e., the complete Phase I in Figure 5-1. The only exception was in D1, where during the five minutes at -45 kV the ‘PD overdriven’ message occurred once. The data filter of 5 pC was also selected to exclude PDs which might have been brought by the ramp up from -45 kV to -56 kV, i.e., Phase II in Figure 5-1. Figure 5-8 shows the maximum PD magnitude in each second plot against tree
length in group D. The three axes, i.e., time in seconds, maximum PD magnitude in pC and tree length in µm share the same scales in each sample for easy comparison; t = 0 s indicated when the DC source began to ramp up from -45 kV to -56 kV, therefore the time point with black arrows t = 11 s was when it reached -56 kV.

Figure 5-8 Maximum PD magnitude in orange plot against tree length in blue in group D, circled points in (a) indicates PD overdriven with PDs higher than 500 pC recorded and red arrows in (e) and (f) indicate channels grew beyond FoV.
Like in group C, the PD occurrence rate was also very low in group D, with usually one PD event in one second if there were any. However, all the samples in group D recorded PD signals before the appearance of initiation channels: sample D1 with the longest initiation length of 428 $\mu$m had PD overdriven occurring twice, as circled in Figure 5-8(a); sample D2 and D3 with 300-400 $\mu$m initiation lengths had PDs lower than 100 pC; sample D4 and D5 with the shortest initiation length of 30-50 $\mu$m had PDs of 5-10 pC. PD signals also accompanied some steps of tree growth after initiation. Channels propagated much faster in group D which were stressed at -56 kV and grew for less than ~60 seconds than in group C which were stressed at -45 kV and developed similar lengths after ~250 seconds. Moreover, PD magnitudes were also higher in group D (higher than 500 pC in D1 and ~200 pC in most cases) than in group C (~80 pC as the maximum in the first 60 seconds after initiation, which was the growth time in group D).

5.3 Treeing under Negative DC Superimposed with AC Ripples

Group NS was named for samples which survived from both Phase I at -45 kV and Phase II at -56 kV and were subjected to the superimposition field. Table 5-3 is the summary of electrical treeing in group NS.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Initiation voltage (kV)</th>
<th>Initiation time (s)</th>
<th>Initiation type</th>
<th>Growth time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS1</td>
<td>N60 ± 7</td>
<td>626</td>
<td>AC-like</td>
<td>281</td>
</tr>
<tr>
<td>NS2</td>
<td>N60 ± 7</td>
<td>472</td>
<td>AC-like</td>
<td>191</td>
</tr>
<tr>
<td>NS3</td>
<td>N60 ± 7</td>
<td>366</td>
<td>AC-like</td>
<td>346</td>
</tr>
<tr>
<td>NS4</td>
<td>N60 ± 7</td>
<td>2050</td>
<td>AC-like</td>
<td>11</td>
</tr>
<tr>
<td>NS5</td>
<td>N60 ± 7</td>
<td>2266</td>
<td>AC-like</td>
<td>33</td>
</tr>
<tr>
<td>NS6 *</td>
<td>N59.8 ± 6.7</td>
<td>-59</td>
<td>AC-like</td>
<td>318</td>
</tr>
<tr>
<td>NS7</td>
<td>N60 ± 7</td>
<td>5705</td>
<td>AC-like</td>
<td>553</td>
</tr>
<tr>
<td>NS8</td>
<td>N60 ± 7</td>
<td>369</td>
<td>AC-like</td>
<td>637</td>
</tr>
<tr>
<td>NS9</td>
<td>-</td>
<td>&gt; 37704</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The AC-like initiation type refers to the initiation length in the range of 5-15 $\mu$m as in AC fields in a gradual way; the growth time is from initiation to one source switching off (more detail in Section 5.3.3) while in sample NS9 without initiation it was the voltage
application time at ‘N60 ± 7’ before one source switched off, which lasted 10 hours and 28 minutes. Sample NS6 was initiated at ‘SDC -56, SAC 11pk’ → ‘N59.8 ± 6.7’ but stressed at ‘N60 ± 7’ following the standard voltage application procedure in Figure 5-1.

5.3.1 Slim Bouquet Structure at ‘N60 ± 7’

Figure 5-9 displays tree images of NS1-9 at the 11th min of growth (the growth time of NS4) and those before one source switched off.

![Figure 5-9 Tree images of sample NS1-8 at various times, scale bar of 100 µm applies in all.](image-url)
While having similarities of tree channel diameter broadening as in AC fields, trees grown at ‘N60 ± 7’ had confined lengths well shorter than 200 µm even with electrical stress lasting 10 hours and 46 minutes in sample NS9, as shown in Figure 5-9(h-2). Furthermore, the tree structure spread a restricted width narrower than 100 µm. However, the most distinct feature was that tree channels in 2D projections would develop into overlapping each other in the end and fully covering the whole pixels of the treeing area. The structure is significantly different from not only branch trees in DC fields and AC fields, which propagate longer and broader and have space between channels in 2D images, but also from bush trees in AC fields as shown in Figure 5-10(a). Bush trees only have the pixels around the needle tip fully covered by overlapped channels, whereas in tree structures at ‘N60 ± 7’ most pixels are fully covered. Moreover, a bush tree can be enveloped by a circle as shown in Figure 5-10(a), compared with the structure enveloped by an ellipse. The structure assembles a flower bunch or a bouquet in a medium tall neck vase, as shown in Figure 5-11 where there is no space between stems in the flowering area. Therefore, this structure is named ‘slim bouquet’ to distinguish from the typical branch or bush structures in AC fields.

(a) bush tree at 15 kV pk [42]  
(b) NS8 at ‘N60 ± 7’

Figure 5-10 Comparison of (a) bush tree in AC fields [42] and (b) tree structure at ‘N60 ± 7’

Figure 5-11 A bouquet in a medium tall neck vase

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Chapter 5: Treeing in Negative DC Fields and under Negative DC Superimposed with AC Ripples

Trial sample TN3 in Table 5-1, which initiated ~2 minutes at ‘N60 ± 7’ after half an hour at ‘N60 ± 5’ and ‘N60 ± 6’ respectively without initiation, grew at ‘N60 ± 7’ for 148 minutes after initiation and resulted in tree channels similar to NS5, as shown in Figure 5-12. The channel propagated a limited distance in length though new branches appeared, and the tree structure broadened within a narrow width.

![Tree growth in TN3 at ‘N60 ± 7’ with different initiation procedure](image)

**Figure 5-12** Tree growth in TN3 at ‘N60 ± 7’ with different initiation procedure

The length growth plot over time for the tree structure grown at ‘N60 ± 7’ shows that the curve commonly employed in AC fields (Figure 1-7) does not represent tree growth. As shown in Figure 5-13, though all samples exhibited a rapid growth in the early stage, they appeared to cease propagating in length after half an hour except NS3 which ceased after two hours. However, treeing ageing continued by broadening the existing channels, which eventually resulted in the slim bouquet structure. The shaded area in sample NS3 in Figure 5-13(a) indicated the lack of image data. This occurred as there were two LabVIEW programmes sharing the CCD camera, one capturing real-time images and the other measuring light emission by PD using a longer exposure time. By human error, after running the program to measure light emission in sample NS3, the program which captured real-time images was not re-enabled.
The treeing area was calculated to describe the channel development in a more explicit way. Images were firstly binarised (using grey scale thresholding functions available in MATLAB), as shown from Figure 5-14(a) to (b), then were aligned with an early-stage image including only the bare needle tip to do the image subtraction to result in (c), which also confirmed that some of the erosion area around the needle tip occurred above it. Treeing area was calculated by counting the number of the white pixels which was later multiplied by the unit area one pixel covered. Figure 5-14(d) is an example to display the fitting between the grey scale image and the binarised one.

Figure 5-13 Tree length of group NS at ‘N60 ± 7’: NS1 in solid black, NS2 in solid orange, NS3 in dashed black, NS4 in solid light green, NS5 in solid magenta, NS6 in solid purple, NS7 in dashed blue, NS8 in dashed red.

Figure 5-14 Example of image binarisation in NS8, scale bar of 100 μm in (a) applies to all.
It should be noted that images in early growth were not binarised due to the thin and light-in-colour channels. In other words, the binarisation algorithm which worked for most of the images failed to binarise the early-stage ones. It explained why there was no data at the initiation moment and minutes after it in the treeing area plot in Figure 5-15.

A developing trend of treeing area over time was spotted in Figure 5-15, which made a better tool to describe treeing ageing than the length which ceased propagating after 0.5-2 hours. Sample NS1 showed a ceased treeing area growth. Sample NS3 which had the longest rapid growth time also had the largest treeing area. Sample NS4 was not included in the area plot as it only included a single branch; NS5 was not included either as it had a structure with two channel clusters too close to one another as shown in Figure 5-16 which also failed the proper binarisation of images.

Figure 5-15 Treeing area of group NS at ‘N60 ± 7’: NS1 in solid black, NS2 in solid orange, NS3 in dashed black, NS6 in solid purple, NS7 in dashed blue, NS8 in solid red, t=0 was the initiation time.

Figure 5-16 Sample NS5 with channel clusters close to one another
With image binarisation the fractal dimension of tree structures can be calculated. This work employed box counting method, the code of which is available online in MATLAB community [144], to get the scatter data set \((r, N(r))\). The slope of the fitted line by linear regression is the fractal dimension of the tree. Taking the last image stressed at ‘N60 ± 7’ in NS8 (i.e., Figure 5-14) as an example, Figure 5-17(a) displays the data set which exhibits the fractal property locally over the first six pairs; Figure 5-17(b) shows the curve fitting using linear regression with the first six data pairs and Figure 5-17(c) evaluates the linear regression model with confidence bonds with RMSE = 0.0733 (root mean squared error). Based on Figure 5-17, \(D_f\) was calculated to be 1.82 for NS8. The calculation and evaluation for NS1, NS2, NS3, NS6 and NS7 are available in Appendix V.

![Figure 5-17](image)

(a) \(N(r)\) plot against \(r\)  
(b) linear regression using the first six data pairs  
(c) linear regression evaluation

*Figure 5-17 2D Fractal dimension calculation and evaluation in NS8*
Table 5-4 lists the summary of $2dD_f$. Except NS2, the fractal dimension of slim bouquet structures in group NS all fell in the range between 1.72 and 1.82, which coincides with the fractal dimensions of dense bushes (S3 and S5 with $2dD_f \text{average} = 1.76$ and 1.79 respectively) in epoxy resins in Table 2-7.

<table>
<thead>
<tr>
<th>Sample</th>
<th>NS1</th>
<th>NS2</th>
<th>NS3</th>
<th>NS6</th>
<th>NS7</th>
<th>NS8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2dD_f$</td>
<td>1.73</td>
<td>1.59</td>
<td>1.80</td>
<td>1.72</td>
<td>1.72</td>
<td>1.82</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.086</td>
<td>0.101</td>
<td>0.080</td>
<td>0.090</td>
<td>0.079</td>
<td>0.073</td>
</tr>
</tbody>
</table>

It is worth mentioning here that $2dD_f$ was not presented for trees initiated and grown at pure DC voltages (both positive and negative) due to the difficulty in getting proper binarised treeing images mainly for two reasons: one is that the channels are too light in colour to give a proper contrast against the background grey level and the other is the contamination explained in Section 4.2.1.

### 5.3.2 PD Signals in Group NS

In group NS, including sample NS9 without initiation, no PDs higher than 5 pC were recorded in Phase I at -45 kV, except NS2 and NS7 which both had PD overdriven occurring once during the five-minute stress at -45 kV and NS6 which had one PD event of 10 pC. However, in Phase II at -56 kV ‘PD overdriven’ occurred in all samples and it continued to occur in Phase III during AC ramp up and Phase IV at ‘N60 ± 7’ where it occurred much more frequently in negative half cycles than in positive half cycles. Its occurrence seemed random and had no identified patterns: it could become less frequent over time in some samples while not in some others; the occurrence rate on average also varied from one in hundreds of seconds to one in thousands of seconds in different samples. These signals are considered an intrinsic phenomenon at higher voltages in more robust samples given that group NS survived from Phase I at -45 kV and Phase II at -56 kV. It is thought to be caused by the local breakdown in some of the free volume in polymer microstructure when stressed at -56 kV or even higher ‘N60 ± 7’ to
result in -67 kV periodically. It is suggested that these PD occurred without tree initiation, near the needle tip in areas of low density, and in the hollow channels when trees had initiated. Very sporadically in some of group NS there were several PD events in the range of 100-500 pC.

With the signals mentioned above excluded, PRPD patterns became available in some samples. When the CPL 542 is connected in series with the test sample in pure AC fields, the background noise level can be supressed to as low as 0.35 pC [53]. Figure 4-9 has previously shown that such PD signals were an indicator of tree channels shortly after initiation, whereas in this superimposition field of negative DC and AC voltages, the background noise was ~4.0 pC measured by the HFCT. It happened that there were tree channels well in development seen through the CCD camera, but no useful PDs could be recorded. Channels at ‘N60 ± 7’ needed to reach a certain length before PRPD could be described for the first time. Table 5-5 lists the existence of the PD clusters, where \( L_{pd} \) was the length when they first appeared and \( L_f \) was the length before one source switched off if no such clusters formed. The length threshold was 75-90 µm and few cycles had more than two PD events recorded with ~4 pC as the background noise level. Therefore, PSA plots, which require at least two PD events in one cycle, were not available in group NS.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>&gt; 4.0 pC PDs?</th>
<th>( L_{pd} ) (µm)</th>
<th>( L_f ) (µm)</th>
<th>Maximum PD number (/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS1</td>
<td>yes</td>
<td>88</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>NS2</td>
<td>no</td>
<td>-</td>
<td>85</td>
<td>-</td>
</tr>
<tr>
<td>NS3</td>
<td>yes</td>
<td>75</td>
<td>-</td>
<td>108</td>
</tr>
<tr>
<td>NS4</td>
<td>no</td>
<td>-</td>
<td>72</td>
<td>-</td>
</tr>
<tr>
<td>NS5</td>
<td>no</td>
<td>-</td>
<td>68</td>
<td>-</td>
</tr>
<tr>
<td>NS6</td>
<td>yes</td>
<td>80</td>
<td>-</td>
<td>91</td>
</tr>
<tr>
<td>NS7</td>
<td>yes</td>
<td>92</td>
<td>-</td>
<td>96</td>
</tr>
<tr>
<td>NS8</td>
<td>yes</td>
<td>90</td>
<td>-</td>
<td>107</td>
</tr>
<tr>
<td>TN3</td>
<td>no</td>
<td>-</td>
<td>73</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5-18 shows the PRPD plot over the first hundreds of seconds and the corresponding tree growth when PD clusters formed a pattern before PD events were buried in the background noise band again. Given the ~4 pC background noise level the
PRPD plot is considered as ‘chopped’ wing-like clusters, and it is associated with channel propagation and darkening in the tree structure which occurred within the corresponding time period.
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For comparison, Figure 5-19 shows the PD magnitude variation trend of an air gap free LDPE sample at 8.4 kV pk AC over treeing time while Figure 5-20 shows that of NS1, NS3, NS6, NS7 and NS8 after the PD clusters in Figure 5-18 appeared, and the plot on the right-hand side, if there is one, is the part shaded in orange on the left-handed side in the range of 4-20 pC as PDs of 20-70 pC appeared to occur sporadically. In the pure AC field, with air gap free samples, the PD magnitude variation was smooth, whereas that in the superimposition fields of a very high DC with AC ripples had the comb-like appearance (the squared and numbered parts in Figure 5-20(a) as an example), which indicates PD events with higher magnitudes than the previous seconds could occur sporadically but did not form PRPD clusters.
Chapter 5: Treeing in Negative DC Fields and under Negative DC Superimposed with AC Ripples

Figure 5-19 PD magnitude trend in an air gap free LDPE sample at 8.4 kV pk AC

(a) NS1

(b) NS3

(c) NS6
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Figure 5-20 PD magnitude variation after PD clusters appeared in (a) NS1, (b) NS3, (c) NS6, (d) NS7 and (e) NS8.

The PD magnitude trends in Figure 5-20 seem a superimposition of those in group C in Figure 5-7 under pure negative DC stresses and that in pure AC fields in Figure 5-19. Sample NS1 had the fewest PD events and the lowest magnitudes; particularly in the time period #3 in Figure 5-20(a) there was only one PD event in one second if the PD number was not zero, and those 10-16 pC signals occurred in the negative half cycles around the phase angle 270° when the voltage was -67 kV at its highest. This agreed with the ceased treeing area development in NS1 shown in the zoomed-in square in Figure 5-15 as there were no continuous PDs which kept eroding the existing tree channels. Sample NS3, which had the largest treeing ageing area shown in Figure 5-15, had larger magnitudes and a relatively smooth trend like in AC fields. Sample NS6, NS7 and NS8 behaved similarly to NS3 but with lower magnitudes and more occurrence of comb-like behaviour. It should be noted that time period #2 in sample NS1 (from the 204th min to the 249th min) was also comb-like, however, there was tree growth over this time, as circled in Figure 5-21. It is thought that there were ‘effective’ PD clusters
which were buried in the background noise band (~4 pC) and it was those clusters that had ‘effectively’ driven tree degradation. Whereas in time period #3, no such PD clusters were buried in the noise band.

![Image comparison of tree structure in sample NS1 over time period #2 in Figure 5-20.](image1)

Figure 5-21 Image comparison of tree structure in sample NS1 over time period #2 in Figure 5-20, scale bar of 100 µm applies in both

There was one type of PD clusters concentrating in phase degrees 0-45° in positive half cycles, as shown in Figure 5-22, where NS3 lacks image date at the time and (e-g) display images of NS6, NS7 and NS8 at the corresponding times.

![PD magnitude vs. phase angle plots](image2)

(a) NS3 of 18105-18225 s  
(b) NS6 of 9850-9910 s  
(c) NS7 of 26485-26605 s  
(d) NS8 of 13175-13205 s
The phase concentration was between 15° and 35° (determined by histogram plots of PD events against phase) in the figure with the voltages between -56 kV and -58 kV. The phase range could be wider within minutes before and/or after the moments shown in the figure but fell in the 10-45° range. This type of cluster only began to occur after hours of tree growth when channels immediately in front of the needle tip had well overlapped, including NS3 which had similar overlapped channels more than one hour earlier as shown in Figure 5-22(h). This cluster did not appear in NS1 which only grew for 281 minutes. It was not a steady pattern like wing-like PDs which could last over the treeing time, and it does not seem to be a chopped wing-like clusters either, otherwise there would have been PDs in phase degrees 45-90° rather than 0-45°. On the contrary, PDs were distributed between 240-270° instead of between 180-240° in negative half cycles.

Though light emission measurements were conducted from time to time in various samples, no images were obtained which could succeed in locating tree channels filled with PDs like those shown previously in Figure 2-48 and Figure 2-50. This is attributed to the low PD magnitude level in group NS.

5.3.3 Further Fine Channel Growth from Existing Structure during DC Ramp Down

Though tree channels ceased propagating in length at ‘N60 ± 7’ even with long-term voltage application, further fine channel development was induced from the existing tree structure during the DC ramp down at 1.0 kV/s in all samples, regardless of the
length and treeing area of the existing structure, and no matter whether there was an AC voltage superimposed onto it or how much the peak value of the AC component was (in order to explore the effect of AC components on fine channel development, the DC source was the first voltage supply to be switched off in some samples while in others the AC source was). Therefore, images labelled (x-2) in Figure 5-9 and Figure 5-12 were ones immediately before the first source voltage, no matter which one, began to fall, and the length plot in Figure 5-13 did not include DC ramp down process. The AC source was decreased at 1.0 kV/step and within each step there was a 30-second waiting period. Figure 5-23 shows the images of the further developed fine channels. It is worth mentioning that ‘deep’ post-process especially sharpening was applied upon the images including the fine channels as they were very thin and light in colour and the image right before one source switched off was displayed to its left using the same image post-process as comparison. For sample NS1, NS4 and TN3 the DC source was decreased to zero before the AC source was, hence during DC ramp down there was still 7 kV pk AC across the sample; for sample NS2 the AC source was decreased to 2 kV pk first (leaving 1.2 kV pk AC across the sample) before the DC source ramped down; for the rest of the samples the AC source was decreased to zero first.
It can be seen from Figure 5-23 that fine channels developed from more than one end of the existing structure and downwards into various directions. Though it was challenging to accurately locate the end of the fine channels, the length showed a trend of being longer than the existing trees in length. Sample NS3 which had the longest existing channels appeared to have the longest fine channels to make the total length of approximately 350-450 µm. It was comparable to the longest initiation length of 428 µm in sample D1 which initiated at -56 kV. The fine channel development was a gradual process, and they began to appear visually when the DC source decreased to the range of -30 to -20 kV. During the DC ramp down process there were sporadic PD events of <20 pC, however, no links were found between the further fine channels and PD activities. Furthermore, an existing tree structure was the precursor to the further fine
channel development as it did not occur in sample NS9 without initiation when the AC source decreased before the DC source did.

In sample NS4 with 7 kV pk AC still across the sample during DC ramp down, tree growth and the corresponding PD activity were seen during AC ramp down, as shown in Figure 5-24. Before this PDs never formed a cluster during the 11 minutes at ‘N60 ± 7’. PDs were extinguished when the AC component across the sample dropped to 5.4 kV pk with the AC source decreasing from 10 kV pk to 9 kV pk. In NS1, NS2 and TN3 which also had an AC component when DC was ramped down, no PD clusters like those in Figure 5-24 occurred.

(a) tree images in the end of DC ramp down (left) compared to in the end of AC ramp down (right) in NS4

(b) PD activities during AC ramp down in NS4

As mentioned previously in Section 2.7.3, fine channels are widely reported in the glassy epoxy resin. They grow under AC voltages with channels having diameters less than 1 µm but are not accompanied by measurable PD signals [118]. Fine channels forming during DC ramp down in this work are thought to have similar properties in terms of the channel diameter and PD signals. Figure 2-54 in Section 2.7.3 also displays two images
claiming fine channels in LDPE. Note that Figure 2-54(a) (replotted as Figure 5-25(a) with a zoomed-in zone) has a very large tip to plane distance \( d = 10 \text{ mm} \) \cite{40}) to result in a bush-branch structure. Hence, the present author’s belief is that in a bush-branch structure there is a chance of fine channel growth (circled in red in (b)) among the branch structure in front of the bush structure. However, the channels in this work during DC ramp down appear morphologically ‘finer’ than reported in \cite{26} under AC voltages.

![Figure 5-25 Comparison of fine channels in LDPE, (b) and (c) shares the scale bar.](image)

### 5.3.4 Case Study 1: Sample C3 at ‘N45 ± 7’ with DC Initiation Channels

Sample C3 is presented as a case study to further the understanding of treeing in a superimposed field, given that C3, after initiation and growth at -45 kV for two hours, continued being stressed at ‘SDC -40.8, SAC 11.4pk’ \( \rightarrow \) ‘N45 ± 7’ for another 230 minutes. No ‘PD overdriven’ (i.e., no PDs higher than 500 pC) occurred during the whole process. Figure 5-26 shows the PD magnitude trend where there was comb-like behaviour in sample C3, as the case in group NS at ‘N60 ± 7’ and after ~170 minutes PD clusters went into extinction as in NS1. Compared with group NS which had shorter AC-type initiation channels and PD magnitudes of ~8 pC in Figure 5-20, C3 had higher PD magnitudes of ~14 pC. Figure 5-27 shows the existing DC channels becoming darker over time from (a) to (c) and a tiny newly developed branch in (d), together with the PRPD pattern variations over time. The phases where PD events occurred in the negative half cycles shifted and became more concentrated around 180° and 270° from (a-b) to (b-c) while the existing channels becoming darker, and when the tiny new branch appeared PDs of much lower magnitudes accompanied.
5.3.5 Case Study 2: Volume Rendering of Sample NS8

To gain a better understanding of the slim bouquet structure, sample NS8 was machined using an Omegapol polisher into the shape shown in Figure 5-28 to be scanned by Micro-XCT (Xradia 520 Versa, Zeiss) and subjected to volume rendering. Two different scanning settings were employed and are listed in Table 5-6. Setting A used pixel binning to generate superpixels and an objective lens with a smaller magnification (20x) than Setting B (40x), therefore leading to a bigger pixel size and a broader physical size...
scanned in Setting A. Both settings had the height taller than 211 µm to include the
volume where fine channels in Figure 5-23(h) were located. Moreover, the number of
projections was smaller and the exposure time for each projection was shorter in Setting
A than in Setting B, resulting in a shorter total scanning time. Setting A was employed to
do a quick reconstruction and Setting B to possibly explore details. Therefore, figures in
the main body are from Setting B and relevant figures from Setting A can be found in
Appendix VI.

A TXRM file including image stacks in xy, xz and yz planes were exported on completion
of scanning. With the differences in Table 5-6, Setting A yielded a 1.8 GB TXRM file and
Setting B 12.8 GB. A piece of software called Avizo was then employed to do image
processing and volume reconstruction. Subvolume extraction is usually the first step
after importing a TXRM file into Avizo, especially when the file is large in size. It provides
a 3D box to extract the volume of interest from the entire raw data, reducing the data
amount to be processed in following steps. Image processing is the next step and Avizo includes grey level modification and many image filters [108]. In this work, histogram scaling was selected to cover the whole range of intensity distribution in images to generate a proper display as shown in Figure 5-29(a); then the built-in filter ‘3D Median’ (a nonlinear digital image filter to reduce noise levels while preserving edge features by calculating as an output the median pixel values, instead of the mean pixel values [145]) was chosen in the ‘Filter Sandbox’ module to reduce the background noise, resulting in Figure 5-29(b). It would facilitate segmentation in the next step. Pixels dark in colour were tree channels, as hollow channels were lower in density than the LDPE base and allowed higher X-rays radiation intensity on the detector. The white edge enhancement around the dark pixels in the figure was introduced by the phase contrast illustrated and explained in Figure 3-11 and Figure 3-12 in Section 3.2.2.

It is known from Table 5-4 in Section 5.3.1 that the slim bouquet structure has a similar $D_f$ value as dense trees in epoxy resin (S3 and S5 in Figure 2-44, i.e. U5 and U7 respectively in [108]). Figure 5-30(a) displays one slice from xy plane in S5 and (b) is a zoomed-in zone from (a) to share the scale bar in (c) from NS8. It shows that the slim bouquet structure is confined within a very limited area in xy plane and has well interconnected ‘islands’ (dark pixel clusters) other than isolated islands as shown in S5.
Figure 5-31 displays one \( xy \) slice from S3 which exhibits interconnected islands like in NS8, though it spreads a much larger degradation area in \( xy \) plane than in NS8. It indicates though both are dense trees, S3 and S5 have different degradation types and the slim bouquet structure shares some similarity with S3. Moreover, nano-XCT might be a more powerful tool for volume rendering of slim bouquet structures based on the image quality shown in Figure 5-31.

Following the image processing is the segmentation where different materials (based on the pixel grey level) are separated and assigned to different layers. Segmentation should be operated as automatically as possible, especially for less experienced users [108].
‘Threshold’ (with the global threshold value set manually in the software interface) and ‘Top-hat’ are the common tools to select tree channels [108][135]. Interactive top-hat transform can be considered threshold calculated locally if the simple thresholding fails to distinguish areas of interest from non-uniform background grey levels [146]. In this work, it was ‘Top-hat’ that picked up pixels of tree channels when the global ‘Threshold’ failed. Then the ‘Magic Wand’ tool successfully selected the needle. This is a region growing algorithm starting from a ‘seed’ to grow into a bigger area within a given tolerance range based on a grey value; the range and the grey value can be set in software interface [147]. ‘Remove islands’ three-dimensionally (removing isolated voxels which are smaller than a certain voxel size and the voxel size can be set in the software interface) was then employed to remove those isolated and small size volumes left by ‘Top-hat’. Figure 5-32 shows the tree channel pixel masking after segmentation, taking the slice in Figure 5-29 as an example.

![Figure 5-32 Illustration of tree channel masking](image)

Figure 5-33 shows the volume rendering displayed from different angles in the software and (d) includes the slice displayed in the previous figures. The needle tip distortion shown in the figure was introduced during sample polishing when the needle trunk was what one could hold to press the LDPE sample onto the sanding paper.
Figure 5-33 Volume rendering of NS8, [units] is µm and generated automatically based on scanning setting.

Figure 5-34 shows the polymer damage which indicates the needle tip was once forced to leave the original position, leaving damage to both needle tip and the polymer. The needle tip had no defects after insertion and its 2D XCT image can be found in Appendix VII. Figure 5-34 also explains the gap between the tree structure and the needle tip (or the needle going downwards to detach from trees) in the volume rendering in Figure 5-33. The projection of the xz plane in Figure 5-33(a) is not necessarily the same as images captured by the CCD camera during tree growth, as the sample could be placed with different angles to the CCD detector and to the X-ray detector in two different
scenarios. The volume rendering shows more details than CCD camera images, especially from the \(yz\) plane. The feature in the structure still holds of the narrow width (<100 \(\mu m\)) concluded previously in Section 5.3.1, though ‘side’ branches circled in Figure 5-33 (b) can exist.

![Image](image1.png)

(a) no polymer damage  
(b) polymer damage

**Figure 5-34** Polymer damage caused by needle during sample polishing

Fine channels in 2D images in Figure 5-23(h) failed to emerge in the volume rendering. Figure 5-35(a) shows one slice at the top including the cross-section of tree channels as two black dots and (b) is the slice \(~5 \mu m\) above (a) with (c) to indicate the positions of these two slices. It illustrates fine channels fail to present themselves. The reason is thought to be that these channels are too thin to show distinguishing pixel intensity from the background.

![Image](image2.png)

(a) one \(xy\) slice including channels as black dots  
(b) the slice 5 \(\mu m\) above (a)
After segmentation the tree volume was immediately available from Avizo, which was 29342 μm³. Then the 3D information was exported as a file which is compatible with MATLAB to do further calculation. Here presents the $3D_f$ which is 2.42 (RMSE=0.0967). The calculation and linear regression evaluation are shown in Figure 5-36.
The $3dD_f$ is larger than 2 and much larger than its 2D counterpart (2.42 vs. 1.82), as is the case in dense trees forming in epoxy resin (2.33 vs. 1.76 for S3 and 2.16 vs. 1.79 for S5) in Table 2-7 [109]. It indicates the same conclusion as in [109] that for a dense and complex structure the $3dD_f$ is a better tool of description than 2D projections. The relevant calculation and explanation for the differences between Setting A (20x lens) and Setting B (40x lens) is available in Appendix VIII.

5.4 Discussion of Results with Negative DC Involved

It has been reviewed in Section 2.3 that 1) space charge injection and accumulation occur in needle-plane treeing geometry in pure DC fields; 2) positive and negative space charges have differences in nature and are described as holes and electrons and therefore 3) leads to distinct charge injection behaviour. Electron injection plays a more pronounced role in electrical treeing in negative DC fields than holes do in positive DC fields and leads to more complicated phenomena in this chapter than described in Chapter 4.

5.4.1 Treeing in Pure Negative DC fields

Tree initiation in negative DC fields could occur in a wider range of voltage magnitudes between -45 kV and -56 kV compared to between +43 kV and +45 kV in the positive case. It tended to occur at shorter times (between -3 s and 40 s in negative DC fields compared to hundreds of seconds on average in positive DC fields). Furthermore, negative DC yielded shorter initiation lengths of 20-430 µm compared to >600 µm in positive DC fields. Furthermore, differences in partial discharge signals presented themselves in the treeing process, including prior to initiation and during growth in samples stressed under negative DC stresses.

All these physical properties can be attributed to the differences in nature between electron injection and hole injection. Electrons, rather than holes which are borrowed
from solid-state physics to describe the lack of electrons at certain positions, play the essential role in space charge transportation. Moreover, at a metal-polymer interface the potential barrier for electron injection is usually lower than that for hole injection [62], and therefore larger numbers of electrons and more frequent electron injection are expected to exist in negative DC fields. During the electron injection local breakdown can occur in some of the free volume in polymer microstructures even without tree initiation, especially at voltages higher than -45 kV. When there is local breakdown, no matter occurring in the free volume of polymers as assumed in negative DC fields in this project or within tree channels as in tree growth in AC fields, PD signals are induced and then recorded by the MPD unit. It has been mentioned in Section 4.4 that tree initiation in DC fields is considered as local intrinsic breakdown with energy release leading to electromechanical cracking in polymers in the form of tree channels. With local breakdown (and therefore PD occurrence) comes with the energy release into polymers. However, this energy release does not necessarily result in the formation of tree channels given the differences in microstructures in various samples; instead, it only has the probability to trigger tree initiation, and when it did trigger tree initiation in this work, longer initiation lengths usually followed higher PD magnitudes prior to it, as shown in the semi-log plot in Figure 5-37.

![Figure 5-37](image-url) Semi-log plot of the length of initiation channels against maximum PD magnitude prior to initiation in negative DC fields

The initiation channel formation in turn provided space for the injected electrons to accelerate in and led to the occurrence of PD events with higher magnitudes shortly after tree initiation in group C as shown in Figure 5-7. Over time more electrons were
injected and accelerated in the high electric field induced by -45 kV DC. Some of them gained sufficient kinetic energy to reach the end of tree channels, forming space charge (electron) accumulation around channel tips. A homo space charge area then built up between the needle tip and channel tips to mitigate the electric field in between, which explains why the PD magnitude decreased over time in group C. The longer the initiation length, the longer path for injected electrons to accelerate in, the sooner for some of them to reach the channel tips, forming the homo space charge area. It might explain why the shorter stopping length followed the longer initiation length in Figure 5-6.

In group D, more energy is thought to be dissipated into polymers to result in initiation considering that group D was stressed at a higher voltage than in group C. Greater energy release is also responsible for the wider initial tree structure with longer main channels and more sub-branches, as well as PDs with higher magnitudes. However, group D only grew for a very limited period, and no PD evolution (like in group C) could be identified. Given the PD overdriven occurrence in group NS, it might be unlikely for group D to reach a stage where trees ceased propagating (as the case in group C) in this work with a 2 mm insulation distance. PD overdriven from time to time should have been expected if the tests had continued and the energy released by that would had the chance of leading to total sample failure eventually.

Electron injection and accumulation playing a more pronounced role than holes in tree initiation has been shown in Figure 2-16 of Section 2.2.4: -20 kV superimposed onto 10 kV pk AC reduced initiation time in LDPE by 1~2 orders of magnitude compared to 10 kV pk AC, while the reduction caused by the +20 kV superimposition was mild [42]. It is in the agreement with the more active role played by electrons than holes in pure DC fields.

**5.4.2 Treeing under Negative DC Superimposed with AC Ripples**

Tree initiation at ‘N60 ± 7’ was found to be an AC-like type which developed gradually to from an optically visible length of ~10 µm. It is thought to be caused by the electron
injection and extraction during the periodical AC half cycles in the mechanisms such as photodegradation by EL radiation and the collision between the accelerated electrons and polymer chains, which has been reviewed in Chapter 2.

However, the tree growth, even with very long treeing times (up to more than ten hours), eventually developed into a distinguishing structure with short channels (<200 µm in length) in a narrow width (<100 µm) named as ‘slim bouquet’. On the other hand, LDPE samples with the same geometry at 8.4 kV pk pure AC developed channels longer than 200 µm within ~60 minutes [53]. The slim bouquet had a much bigger $3dD_f = 2.42$ than its $2dD_f = 1.82$, as is the case in dense bush trees in glassy epoxy resins [109]. There were well interconnected ‘islands’ (dark colour pixel clusters indicating hollow channels) in its cross-sections extracted from 3D volume information. The formation of the slim bouquet structure is also thought to be attributed to electron injection and space charge accumulation. As previously shown in Figure 2-55, electron injection from the needle tip into the polymer was found to form an homo space charge area with the moderated electric field around the needle tip [45], within which the AC inceptive trees would be kept enveloped and failed to reach beyond even with 10 hours of pure negative DC stress at -60 kV. In this work the DC component of -60 kV was sufficiently high to form the same space charge ‘shielding’ area, which meant tree channels would be confined in terms of length and width. Meanwhile with AC ripples across the sample, there were PDs eroding the existing channels. The electrical ageing within the limited length and width would not surprisingly result in a slim bouquet structure. Its formation without sample failure at ‘N60 ± 7’ is thought to agree with prolonged breakdown times in LDPE when -15 kV DC was superimposed onto 15 kV AC pk [42] shown in Figure 2-60 of Section 2.7.5 though be in contradictory with shortened breakdown times at both ‘P15 ± 15’ and ‘N15 ± 15’ in epoxy resin [120]. Again, results naturally vary in different materials and with various $R_{AC/DC}$, $R_{AC/AC_i}$ and $R_{DC/DC_i}$ as explained in Section 2.7.5.

PD signals in the superimposition fields had combined characteristics which are typical in both AC fields and DC fields, especially in group C. There was wing-like PRPD patterns,
though chopped, and comb-like behaviour in the PD magnitude variation trends. The wing-like PD clusters are thought to be the reason for channel widening and darkening, as in the last 80 minutes in sample NS1 ceased PRPD clusters corresponded to the ceased ageing area. The PD signals had their own features at ‘N60 ± 7’ after a long period of voltage application and well overlapped channels as shown previously in Figure 5-22, where PD events concentrated in phase degrees 0-45° rather than 45°-90° in the positive AC half cycles. The phase distribution on the left side in the positive AC half cycles agreed with corona discharges in AC fields in [148], as shown in Figure 5-38. It has also been found that corona discharges could happen in samples with air gaps in our previous work [124]. It is believed that the physical conditions to result in corona discharges could be met within the well overlapped channels in the slim bouquet structure to produce the PRPD pattern shown in Figure 5-22.

The alleviation effect of space charge on the electric field is well represented in sample NS4 where continuous PD clusters only began to appear after the DC source was removed across the sample, as shown in Figure 5-24. The removal of the DC source, therefore the removal of space charge shielding, increased the effective local electric field to reach the partial discharge inception field. Whereas it did not lead to PD clusters.
in sample NS1 and TNS, as well as in NS2. The former is thought to have more conducting channels and the AC component of 1.2 kV pk was too low to incept partial discharges.

The dynamic variation and equilibrium of space charge distribution resulting from DC source removal is thought to be responsible for the further fine channel development during DC ramp down. For simplicity let us assume that the local electric field is the superimposition of 1) statistic electric field which does not take space charge into consideration and is therefore positively correlated with the applied voltage at the needle and 2) the shielding effect or the moderation by the space charge. During the DC ramp down the static field would become lower to alleviate local electric field. Meanwhile space charges (electrons) would also travel back to the needle tip, which would result in the shrinkage of shielding area and increase the local field. The competition between the two would determine what would happen during DC ramp down. Figure 5-39 illustrates the dynamic variation of space charge accumulation during DC ramp down.

With the existing channels there was a space charge shielding area enveloping the tree structure preventing its further propagation in length and width, as shown in Figure 5-39(a). When the DC source began to ramp down, the area shrunk and when it became

![Figure 5-39 Variation of space charge distribution during DC ramp down](image-url)
smaller than the existing channels it would not shield the channel tips anymore, as shown in Figure 5-39(b). The increase of local electric field induced by the loss of the shielding effect is thought to be more considerable than the static field decrease induced by the voltage ramping down, which resulted in the local field increase around the channel tips and drive fine channels to propagate. With DC ramping down continuously, the area would further shrink and induce further fine channels development as shown in Figure 5-39(c). No links could be identified between fine channel growth and the sporadic PD events of <20 pC; therefore, their formation is thought to result from the electromechanical stress induced by local electric field as in epoxy resin [119].

It should be noted that 1) sample NS9 without tree initiation after ~10.5 hours at ‘N60 ± 7’ did not develop fine channels during DC ramp down, 2) samples without initiation after six hours at pure positive DC voltages (Section 4.2) did not develop fine channels during DC ramp down, and 3) samples PS2, PS3, PS4 and PS8 without tree initiation after six hours at ‘P45 ± 5’ (Section 4.3) did not develop fine channels during DC ramp down either. Moreover, initiated samples at pure positive DC voltages did not develop fine channels during DC ramp down, as the initiation channels were very long (>600 µm) already. It indicated that a short existing tree structure (or short tree-like defects) were the precursor to fine channel development during DC ramp down, and the dynamic change in local electric field around the existing channel tips was the reason for further fine channel propagation.

Comparing group NS at ‘N60 ± 7’, which had shorter AC-type initiation and limited tree length growth and PD magnitudes of ~8 pC in Figure 5-20, with sample C3 at ‘N45 ± 7’ which had higher PD magnitudes of ~14 pC in Figure 5-27, the difference in PD magnitude might be also caused by the lesser shielding effects which was brought by -45 kV compared to -60 kV.

With regard to the PRPD variation in sample C3, it is thought to be attributed by the conductivity change within the DC initiation channels. With the erosion of partial
discharges, the existing DC initiation channels became more conductive, suppressing PD activity within the channels, which eventually lead to PDs with lower magnitudes which were only associated with the newly formed tiny branches in Figure 5-27(d).

### 5.5 Conclusions with Negative DC Involved

Tree initiation and growth in negative DC fields and under negative DC superimposed with AC ripples were investigated and the role of electron injection with negative DC involved was discussed in this chapter. The conclusions were as follows,

1) Electrical treeing in negative DC fields had different characteristics from that in positive DC fields. The former occurred over a wider range of voltage magnitudes within a shorter initiation time and had a shorter initiation length. Considerable step-like tree length propagation was also seen shortly after initiation in negative DC fields.

2) Partial discharges could occur prior to tree initiation in negative DC fields, and in cases with PD occurrence prior to initiation, longer initiation lengths were seen to follow the previous higher PD magnitudes. Variations in partial discharges presented themselves during treeing and had a comb-like appearance in the PD magnitude variation trend but did not form PD clusters. PDs with higher magnitudes occurred at higher voltages without tree initiation.

3) A slim bouquet tree structure distinguishable from the typical branch or bush structures in AC fields appeared under negative DC superimposed with AC ripples. It was short in length and narrow in width, even with long treeing times. In 2D projections channels overlapped each other and eventually fully covered all of pixels of the treeing area, in which case, treeing area was a better tool to describe treeing ageing over time. From 3D volume information, well interconnected islands were seen in cross sections and $3dD_t$ was more representative for a dense and complex tree structure like the slim bouquet.
4) PD signals under negative DC superimposed with AC ripples had the combined characteristics of comb-like appearance as in negative DC fields and wing-like PRPD clusters as in AC fields, as well as its own feature of phase concentration between 0 and 45° in the positive AC half cycles.

5) Further fine channels developed from the existing tree structure when the DC source ramped down in the superimposition fields, no matter whether there was an AC voltage superimposed onto it or how much the peak value of the AC component was and regardless of the length and treeing area of the existing structure.
Chapter 6  Summary of Conclusions

The previous two chapters describe the experimental results in detail and provide explanations in both polarities. This chapter presents a summary of the conclusions. Table 6-1 displays a simplified comparison of experimental results in both polarities. However, it should be emphasised that some of situations are more complicated than a simple yes-or-no one and specific details in Chapter 4 and Chapter 5 will always help.

Table 6-1 Summary of treeing in LDPE (r = 3 µm, d = 2 mm) in various electric fields

<table>
<thead>
<tr>
<th>Field type</th>
<th>AC</th>
<th>+DC</th>
<th>-DC</th>
<th>+DC plus AC</th>
<th>-DC plus AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>8.4 kV pk</td>
<td>+45 kV</td>
<td>-45 kV</td>
<td>-56 kV</td>
<td>P45 ± 5</td>
</tr>
<tr>
<td>Initiation time range (s)</td>
<td>~300 to 12000</td>
<td>-2 to 1636</td>
<td>0 to 40</td>
<td>3 to 2</td>
<td>0 to 41</td>
</tr>
<tr>
<td>Initiation length (µm)</td>
<td>10-20</td>
<td>&gt; 600</td>
<td>20-54</td>
<td>32-428</td>
<td>&gt;1160</td>
</tr>
<tr>
<td>PDs prior to initiation</td>
<td>No</td>
<td>PD not an indicator</td>
<td>Yes, not all</td>
<td>Yes, all</td>
<td>Yes</td>
</tr>
<tr>
<td>Further tree growth?</td>
<td>Yes, gradual</td>
<td>Little</td>
<td>Yes, step-like</td>
<td>Yes, step-like</td>
<td>Catastrophic failure</td>
</tr>
<tr>
<td>Tree types</td>
<td>Mix of branch and bush</td>
<td>Branch</td>
<td>Branch</td>
<td>Branch</td>
<td>Catastrophic failure</td>
</tr>
<tr>
<td>PPRD clusters</td>
<td>Yes</td>
<td>PD not an indicator</td>
<td>No, comb-like</td>
<td>No, comb-like</td>
<td>Yes</td>
</tr>
<tr>
<td>Max. PD (pC)</td>
<td>~30</td>
<td>PD not an indicator</td>
<td>~80</td>
<td>Up to nC</td>
<td>Up to nC</td>
</tr>
</tbody>
</table>

The conclusions in this thesis are summarised as follows,

1) Optically invisible air gaps at the needle-polymer interface were identified to be of 10-55 µm in height in and affect tree initiation and growth in AC fields.

2) In positive DC fields, tree initiation lengths were at least one order of magnitude longer than in AC fields. Little further growth followed such long initiation channels. The initiation voltage was close to the short-term local breakdown voltage and PD measurements were not an indicator of treeing in positive DC fields.

3) At the initiation voltage in positive DC fields, an extra AC ripple as low as 5 kV pk had a chance of causing catastrophic failure to the insulation. PD measurements could
provide useful information under positive DC superimposed with AC ripples. However, special attention should be paid to ensure the insulation safety when AC ripples were applied.

4) Tree initiation in negative DC fields occurred over a wider range of voltage magnitudes within a shorter initiation time and had a shorter initiation length. Considerable step-like growth was observed shortly after initiation.

5) Partial discharges could occur prior to initiation in negative DC fields, and in cases with PD occurrence prior to initiation, longer initiation lengths were seen to follow the previous higher PD magnitudes. Variations in PD signals presented themselves during treeing and had a comb-like appearance in the PD magnitude variation trend. PDs with higher magnitudes could occur at higher voltages without tree initiation.

6) Under negative DC superimposed with AC ripples, a distinct new tree structure appeared and was named ‘slim bouquet’. It was short in length and narrow in width, even with long treeing times. In 2D projections channels became overlapped with each other and eventually fully covered all of pixels of the treeing area, in which case, treeing area was a better tool to describe treeing ageing. Well interconnected islands were seen in cross sections extracted from the volume rendering and $3dDf$ was found to be representative for a dense and complex tree structure like the slim bouquet.

7) PDs under negative DC superimposed with AC ripples had combined characteristics of comb-like appearance and wing-like PRPD clusters featuring in negative DC fields and AC fields respectively, as well as its own feature of phase concentration between 0 and 45° in the positive AC half cycles.

8) Fine channels further developed from the existing tree structure when the negative DC source ramped down. They developed no matter whether there was an AC voltage stayed across the sample during DC ramp down or how much the peak value of the AC
component was. They also occurred regardless of the length and treeing area of the existing structure.

9) Fine channel development during DC ramp down did not occur in samples without initiation structures, regardless of the voltage application types.
Chapter 7  Future Work

Based on what has been investigated, there are several pieces of work which can follow immediately to add more details to this work. For example,

1) SEM can be done in cross sections of the slim bouquet structure to explore details of this structure on the submicron scale. For example, do the channels interconnect with each other, or are they just bundles of thinner channels than micro-XCT can examine? Nano-XCT can also answer the question. The diameter of fine channels can also be determined by SEM or Nano-XCT.

2) Raman spectra on various spots in the slim bouquet tree channels can be done to obtain more insight into the ageing process within the slim bouquet structure in terms of chemical properties, especially if there is residual carbon deposited within channel walls.

3) With knowledge obtained from 1) and 2), to explore treeing models in terms of channel conductivity and space charge accumulation in software such as COMSOL.

4) 3D imaging, preferably by Nano-XCT, on tree channels initiated at -45 kV will also help understand the nature of the tree structure given that 1) there is a paper reporting about the pre-channel formation in tree structures initiated by lightning impulses following negative DC prestress [149] and 2) that tree initiation at -56 kV in this work did have more optically visible sub-branches than that at -45 kV.

5) There has been intensive work on electrical treeing in LDPE at between 8.4 and 15 kV pk AC. Tree initiation and growth in pure AC fields at 5 kV pk AC (to compare with ‘P45 ± 5’), 7 kV pk AC (to compare with ‘N60 ± 7’), +45 kV DC (the maximum voltage in ‘P45 ± 6’) and -67 kV DC (the maximum voltage in ‘N60 ± 7’) will add comparison to this work, making a more detailed ‘map’ of treeing in DC networks.
7) Different DC ramp down rates with existing treeing degradation are also an interesting topic, for example, in terms of further fine channel development to help understand the behaviour of space charge distribution and provide practical information on ‘switching’ events in DC networks, for example, offshore power generation cut off from onshore power network, especially unplanned.

8) During sample fabrication there were samples with natural air gap formation, though not many in number. They can also be stressed with the identical process as some of the tests mentioned in previous chapters to find out if a naturally formed air gap affects DC treeing in LDPE. Furthermore, if larger artificial gaps affect DC treeing in LDPE. These will provide understanding of the effect of interfaces on treeing in DC networks.

9) This work employed AC voltages at 50 Hz, the effect of AC harmonics (for example 3x, 5x...caused by power converters [11]) plus a high DC voltage on treeing can also be explored.
Reference


[47] F. Noto and N. Yoshimura, “Voltage and frequency dependence of tree growth in


[92] J.-P. Crine, “Influence of electro-mechanical stress on electrical properties of


[141] Omicron, “MPD 600 Brochure High-end measurement and analysis system for partial discharges.”


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SAFETY DATA SHEET

Revision Date: 19-Feb-2021
Revision Number: 2

SECTION 1: IDENTIFICATION OF THE SUBSTANCE/MIXTURE AND OF THE COMPANY/UNDERTAKING

1.1. Product identifier
Product Description: Polyethylene sheet
Cat No.: 45175
CAS-No: 9002-88-4
Molecular Formula: (CH₂CH₂)

1.2. Relevant identified uses of the substance or mixture and uses advised against
Recommended Use: Laboratory chemicals
Uses advised against: No Information available

1.3. Details of the supplier of the safety data sheet
Company: Alfa Aesar
Avocado Research Chemicals, Ltd.
Shore Road
Port of Heysham Industrial Park
Heysham, Lancashire LA3 2XY
United Kingdom
Office Tel: +44 (0) 1524 850506
Office Fax: +44 (0) 1524 850608

E-mail address: uktech@alfa.com
www.alfa.com
Product Safety Department

1.4. Emergency telephone number
Call Carachem 24 at
+44 (0) 1885 407333 (English only);
+44 (0) 1235 239670 (Multi-language)

SECTION 2: HAZARDS IDENTIFICATION

2.1. Classification of the substance or mixture
CLP Classification - Regulation (EC) No 1272/2008

Physical hazards
Based on available data, the classification criteria are not met

Health hazards
Based on available data, the classification criteria are not met
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Environmental hazards
Based on available data, the classification criteria are not met.

Full text of Hazard Statements: see section 16

2.2. Label elements
None required

2.3. Other hazards
No information available

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS

3.1. Substances

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>EC-No.</th>
<th>Weight %</th>
<th>CLP Classification - Regulation (EC) No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>9002-88-4</td>
<td>&lt;=100</td>
<td></td>
<td>1272/2008</td>
</tr>
</tbody>
</table>

Full text of Hazard Statements: see section 16

SECTION 4: FIRST AID MEASURES

4.1. Description of first aid measures

Eye Contact
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

Skin Contact
Wash off immediately with plenty of water for at least 15 minutes. Get medical attention immediately if symptoms occur.

Ingestion
Clean mouth with water and drink afterwards plenty of water. Get medical attention if symptoms occur.

Inhalation
Remove to fresh air. Get medical attention immediately if symptoms occur.

Self-Protection of the First Aider
No special precautions required.

4.2. Most important symptoms and effects, both acute and delayed
None reasonably foreseeable.

4.3. Indication of any immediate medical attention and special treatment needed

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Notes to Physician
Treat symptomatically.

SECTION 5: FIREFIGHTING MEASURES

5.1. Extinguishing media

Suitable Extinguishing Media
Carbon dioxide (CO2), Powder. Water spray. In case of major fire and large quantities: Evacuate area. Fight fire remotely due to the risk of explosion.

Extinguishing media which must not be used for safety reasons
No information available.

5.2. Special hazards arising from the substance or mixture

Thermal decomposition can lead to release of irritating gases and vapors.

Hazardous Combustion Products
None under normal use conditions.

5.3. Advice for firefighters

As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

SECTION 6: ACCIDENTAL RELEASE MEASURES

6.1. Personal precautions, protective equipment and emergency procedures

Ensure adequate ventilation. Use personal protective equipment as required. Avoid dust formation.

6.2. Environmental precautions

Should not be released into the environment. See Section 12 for additional Ecological Information.

6.3. Methods and material for containment and cleaning up

Sweep up and shovel into suitable containers for disposal. Avoid dust formation.

6.4. Reference to other sections

Refer to protective measures listed in Sections 8 and 13.

SECTION 7: HANDLING AND STORAGE

7.1. Precautions for safe handling

Wear personal protective equipment/face protection. Ensure adequate ventilation. Avoid contact with skin, eyes or clothing. Avoid ingestion and inhalation. Avoid dust formation.

Hygiene Measures
Handle in accordance with good industrial hygiene and safety practice. Keep away from food, drink and animal feeding stuffs. Do not eat, drink or smoke when using this product. Remove and wash contaminated clothing and gloves, including the inside, before re-use. Wash hands before breaks and after work.

7.2. Conditions for safe storage, including any incompatibilities
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Keep container tightly closed in a dry and well-ventilated place.

Technical Rules for Hazardous Substances (TRGS) 510 Storage Class (LGK) (Germany) Class 11

7.3. Specific end use(s)
Use in laboratories

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

8.1. Control parameters

Exposure limits
List source(s):

Biological limit values
This product, as supplied, does not contain any hazardous materials with biological limits established by the region specific regulatory bodies

Monitoring methods
BS EN 14042:2003 Title Identifier: Workplace atmospheres. Guide for the application and use of procedures for the assessment of exposure to chemical and biological agents.
MDHS14: General methods for sampling and gravimetric analysis of respirable and inhalable dust

Derived No Effect Level (DNEL) No information available

<table>
<thead>
<tr>
<th>Route of exposure</th>
<th>Acute effects (local)</th>
<th>Acute effects (systemic)</th>
<th>Chronic effects (local)</th>
<th>Chronic effects (systemic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral Dermal Inhalation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Derived No Effect Level (DNEL) No information available

8.2. Exposure controls

Engineering Measures
Note under normal use conditions.

Personal protective equipment

Eye Protection Wear safety glasses with side shields (or goggles) (European standard - EN 166)

Hand Protection Protective gloves

<table>
<thead>
<tr>
<th>Glove material</th>
<th>Breakthrough time</th>
<th>Glove thickness</th>
<th>EU standard</th>
<th>Glove comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural rubber</td>
<td>See manufacturers</td>
<td></td>
<td>EN 3/3</td>
<td></td>
</tr>
<tr>
<td>Nitrile rubber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neoprene PVC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Skin and body protection Long sleeved clothing.

Inspect gloves before use.

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Please observe the instructions regarding permeability and breakthrough time which are provided by the supplier of the gloves. (Refer to manufacturer/supplier for information)

Ensure gloves are suitable for the task. Chemical compatibility, Dexterity, Operational conditions, User susceptibility, e.g. sensitisation effects, also take into consideration the specific local conditions under which the product is used, such as the danger of cuts, abrasion.

Remove gloves with care avoiding skin contamination.

Respiratory Protection No protective equipment is needed under normal use conditions.

Large scale/emergency use Use a NIOSH/MSHA or European Standard EN 138 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced

Recommended Filter type: Particle filter 2

Small scale/Laboratory use Maintain adequate ventilation

Environmental exposure controls No information available.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

9.1. Information on basic physical and chemical properties

<table>
<thead>
<tr>
<th>Physical State</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>White</td>
</tr>
<tr>
<td>Odor</td>
<td>Odorless</td>
</tr>
<tr>
<td>Odor Threshold</td>
<td>No data available</td>
</tr>
<tr>
<td>Melting Point/Range</td>
<td>104 - 138 °C / 219.2 - 260.4 °F</td>
</tr>
<tr>
<td>Softening Point</td>
<td>No data available</td>
</tr>
<tr>
<td>Boiling Point/Range</td>
<td>No information available</td>
</tr>
<tr>
<td>Flammability (Liquid)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Flammability (solid,gas)</td>
<td>No information available</td>
</tr>
<tr>
<td>Explosion Limits</td>
<td>No data available</td>
</tr>
<tr>
<td>Flash Point</td>
<td>No information available</td>
</tr>
<tr>
<td>Autoignition Temperature</td>
<td>343 °C / 649.4 °F</td>
</tr>
<tr>
<td>Decomposition Temperature</td>
<td>No data available</td>
</tr>
<tr>
<td>pH</td>
<td>No information available</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Water Solubility</td>
<td>Insoluble in water</td>
</tr>
<tr>
<td>Solubility in other solvents</td>
<td>No information available</td>
</tr>
<tr>
<td>Partition Coefficient (n-octanol/water)</td>
<td>Method - No information available</td>
</tr>
<tr>
<td>Vapor Pressure</td>
<td>No data available</td>
</tr>
<tr>
<td>Density / Specific Gravity</td>
<td>0.945 g/cm3 @ 20 °C</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>No data available</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Particle characteristics</td>
<td>No data available</td>
</tr>
</tbody>
</table>

9.2. Other information

Molecular Formula \((\text{CH}_2\text{CH}_2)\)

Evaporation Rate Not applicable - Solid

SECTION 10: STABILITY AND REACTIVITY

10.1. Reactivity None known, based on information available

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10.2. Chemical stability
Stable under normal conditions.

10.3. Possibility of hazardous reactions
- Hazardous Polymerization: No information available.
- Hazardous Reactions: None under normal processing.

10.4. Conditions to avoid
- Incompatible products: Excess heat.

10.5. Incompatible materials
- Oxidizing agent.

10.6. Hazardous decomposition products
None under normal use conditions.

SECTION 11: TOXICOLOGICAL INFORMATION

11.1. Information on hazard classes as defined in Regulation (EC) No 1272/2008

Product Information

(a) acute toxicity;
Oral Based on available data, the classification criteria are not met
Dermal No data available
Inhalation No data available

<table>
<thead>
<tr>
<th>Component</th>
<th>LD50 Oral</th>
<th>LD50 Dermal</th>
<th>LC50 Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>LD50 &gt; 2000 mg/kg (Rat)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(b) skin corrosion/irritation; No data available

(c) serious eye damage/irritation; No data available

(d) respiratory or skin sensitization;
- Respiratory: No data available
- Skin: No data available

(e) germ cell mutagenicity; No data available

(f) carcinogenicity;
No data available
There are no known carcinogenic chemicals in this product

(g) reproductive toxicity; No data available

(h) STOT—single exposure; No data available

(i) STOT—repeated exposure; No data available
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<table>
<thead>
<tr>
<th>Target Organs</th>
<th>No information available.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) aspiration hazard;</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Solid</td>
<td></td>
</tr>
<tr>
<td>Symptoms / effects, both acute and delayed</td>
<td>No information available.</td>
</tr>
</tbody>
</table>

11.2. Information on other hazards

Endocrine Disrupting Properties
Assess endocrine disrupting properties for human health. This product does not contain any known or suspected endocrine disruptors.

SECTION 12: ECOLOGICAL INFORMATION

12.1. Toxicity
Ecotoxicity effects
Contains no substances known to be hazardous to the environment or that are not degradable in waste water treatment plants.

12.2. Persistence and degradability
Persistence
In soluble in water.
Degradability
Not relevant for inorganic substances.

12.3. Bioaccumulative potential
May have some potential to bioaccumulate.

12.4. Mobility in soil
Spillage unlikely to penetrate soil. The product is insoluble and floats on water. Is not likely mobile in the environment due its low water solubility.

12.5. Results of PBT and vPvB assessment
No data available for assessment.

12.6. Endocrine disrupting properties
Endocrine Disruptor Information
This product does not contain any known or suspected endocrine disruptors

12.7. Other adverse effects
Persistent Organic Pollutant
This product does not contain any known or suspected substance
Ozone Depletion Potential
This product does not contain any known or suspected substance

SECTION 13: DISPOSAL CONSIDERATIONS

13.1. Waste treatment methods
Waste from Residues/Unused Products
Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

Contaminated Packaging
Empty remaining contents. Dispose of in accordance with local regulations. Do not re-use empty containers.

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European Waste Catalogue (EWC) According to the European Waste Catalog, Waste Codes are not product specific, but application specific.
Other Information Waste codes should be assigned by the user based on the application for which the product was used.

SECTION 14: TRANSPORT INFORMATION

IMDG/IMO Not regulated
14.1. UN number
14.2. UN proper shipping name
14.3. Transport hazard class(es)
14.4. Packing group

ADR Not regulated
14.1. UN number
14.2. UN proper shipping name
14.3. Transport hazard class(es)
14.4. Packing group

IATA Not regulated
14.1. UN number
14.2. UN proper shipping name
14.3. Transport hazard class(es)
14.4. Packing group

14.5. Environmental hazards No hazards identified
14.6. Special precautions for user No special precautions required
14.7. Maritime transport in bulk according to IMO instruments Not applicable, packaged goods

SECTION 15: REGULATORY INFORMATION

15.1. Safety, health and environmental regulations/legislation specific for the substance or mixture

International Inventories
X = listed, Europe (EINECS/ELINCS/NLP), U.S.A. (TSCA), Canada (DSL/NDSL), Philippines (PICCS), China (IECSC), Japan (ENCS), Australia (AICS), Korea (ECL).

<table>
<thead>
<tr>
<th>Component</th>
<th>EINECS</th>
<th>ELINCS</th>
<th>NLP</th>
<th>TSCA</th>
<th>DSL</th>
<th>NDSL</th>
<th>PICCS</th>
<th>ENCS</th>
<th>IECSC</th>
<th>AICS</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td>KE-2987 7</td>
</tr>
</tbody>
</table>

Not applicable

National Regulations

WGK Classification Water endangering class = 2 (self classification)
Appendix I: Product SDS File of LDPE

SAFETY DATA SHEET

Polyethylene

Revision Date 19-Feb-2021

<table>
<thead>
<tr>
<th>Component</th>
<th>France - INRS (Tables of occupational diseases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>Tableaux des maladies professionnelles (TNP) - RS 66</td>
</tr>
<tr>
<td>UK</td>
<td>Take note of Control of Substances Hazardous to Health Regulations (COSHH) 2002 and 2005 Amendment</td>
</tr>
</tbody>
</table>

15.2. Chemical safety assessment

A Chemical Safety Assessment/Report (CSA/CSR) has not been conducted

SECTION 16: OTHER INFORMATION

Full text of H-Statements referred to under sections 2 and 3

Legend

CAS - Chemical Abstracts Service
EINECS/ELINCS - European Inventory of Existing Commercial Chemical Substances/EU List of Notified Chemical Substances
PICCS - Philippines Inventory of Chemicals and Chemical Substances
IECSC - Chinese Inventory of Existing Chemical Substances
KECL - Korean Existing and Evaluated Chemical Substances
WEL - Workplace Exposure Limit
ACGIH - American Conference of Governmental Industrial Hygienists
DNEL - Derived No Effect Level
RPE - Respiratory Protective Equipment
LC50 - Lethal Concentration 50%
NOEC - No Observed Effect Concentration
PBT - Persistent, Bioaccumulative, Toxic
ADR - European Agreement Concerning the International Carriage of Dangerous Goods by Road
IMO/IMDG - International Maritime Organization/International Maritime Dangerous Goods Code
OECD - Organisation for Economic Co-operation and Development
BCF - Bioconcentration factor
ICAO/IATA - International Civil Aviation Organization/International Air Transport Association
MARPOL - International Convention for the Prevention of Pollution from Ships
ATE - Acute Toxicity Estimate
VOC - Volatile Organic Compound

Key literature references and sources for data
https://echa.europa.eu/information-on-chemicals
Suppliers safety data sheet, Chemadvisor - LOLL, Merck index, RTECS

Training Advice
Chemical hazard awareness training, incorporating labelling, Safety Data Sheets (SDS), Personal Protective Equipment (PPE) and hygiene.

Prepared By Health, Safety and Environmental Department
Revision Date 19-Feb-2021
Revision Summary Update to CLP Format.


Disclaimer

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

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SAFETY DATA SHEET

Polyethylene sheet

Revision Date 19-Feb-2021

End of Safety Data Sheet
Appendix II: Dimensions of Test Cell

Figure Appx. 1 Dimensions of the test cell in Figure 3-26, by courtesy of Dr. Hualong Zheng
Appendix III: Front Panels of LabVIEW Files

(a) HVDC Enable

(b) HVAC Enable with trip-off*

(c) reset HVDC signal to zero

(d) AC control and divider readings (without load)

(e) ramp rate control of DC source

(f) Image capture by CCD camera

* The part squared by purple dashed line is to trip off amplifier based on DC voltage should it fail to trip off itself.

Figure Appx. 2 Front Panels of LabVIEW files
Appendix IV: Simulation of HV Zone Including Divider by PSpice

Note: RC parameters here are calculated based on the input and output impedance therefore different from those shown in main body.

Figure Appx. 3 Equivalent circuit of the HV zone in Figure 3-22 with divider
Appendix V: 2D $D_f$ Calculation and Evaluation in Group NS

(a) $N(r)$ plot against $r$ in NS1

(b) local linear regression in NS1

(c) linear regression evaluation in NS1

(d) $N(r)$ plot against $r$ in NS2
Appendix V: 2D $D_f$ Calculation and Evaluation in Group NS

(e) local linear regression in NS2

(f) linear regression evaluation in NS2

(g) $N(r)$ plot against $r$ in NS3

(h) local linear regression in NS3

(i) linear regression evaluation in NS3

(j) $N(r)$ plot against $r$ in NS6
Appendix V: 2D $D_f$ Calculation and Evaluation in Group NS

- **(k)** Local linear regression in NS6
- **(l)** Linear regression evaluation in NS6
- **(m)** $N(r)$ plot against $r$ in NS7
- **(n)** Local linear regression in NS7
- **(o)** Linear regression evaluation in NS7

Figure Appx. 4 $D_f$ Calculation and Evaluation in Group NS
Appendix VI: Volume Rendering of NS8 from Setting A (20x Lens)

Figure Appx. 5 Volume rendering of NS8 using 20x lens
Appendix VII: 2D XCT Radiograph of NS8 after Needle Insertion

Figure Appx. 6 2D XCT radiograph of NS8 after needle insertion and before treeing
Appendix VIII: $3dD_f$ Calculation and Evaluation of NS8 from Setting A (20x Lens)

![Graphs and images showing calculation and evaluation of $3dD_f$.]

(a) $N(r)$ plot against $r$ in NS8 ($3dD_f$)
(b) Local linear regression in NS8 ($3dD_f$)
(c) Linear regression evaluation in NS8 ($3dD_f$)

Note:

1) $3dD_f=2.24$ (RMSE=0.101). As is the case in Setting B, the fractal property applies in (a) locally. Here the standard is to ensure the RMSE is smaller than ~0.1. The linear regression can be done with all points in (a) included, but in that case different samples have different RMSE values, and they vary from 0.079 to 0.262. Moreover, box counting is affected by the dimension of the 2D image or the 3D reconstruction: the bigger the size $r$, the bigger error $N(r)$ has. Therefore, points circled in (b) tend to be a bad fit or outliers. This is why the standard here is RMSE other than fitting all points into a linear regression.

2) The tree volume from Setting A (20x) was $36547 \, \mu m^3$, which is sensible considering the 4 times difference in voxel size ($0.44 \, \mu m$ vs. $0.11 \, \mu m$ and therefore $4^3$ times difference in the minimum volume box or the spatial resolution) between two settings.

Figure Appx. 7 $3dD_f$ Calculation and Evaluation of NS8 from Setting A
Appendix IX: List of Publications

Journals


Conference papers


