PARTIAL DISCHARGE AND STREAMER CHARACTERISTICS OF TRANSFORMER LIQUIDS UNDER AC STRESS

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Abstract

Pre-breakdown phenomena in transformer liquids have been extensively investigated. The published work can be broadly categorised into streamer and partial discharge (PD) studies, with the former focusing on physical nature and the latter being more relevant to industrial applications. Mineral oil, as the dominant candidate, has been used in power transformers for over a century. In the past decade, there has been an increasing interest in filling power transformers with alternative liquids, e.g. esters and gas-to-liquids (GTL) based oils. This work aims to correlate the PD and streamer characteristics of three transformer liquids under AC stress. The liquids include a conventional mineral oil (Gemini X), a GTL oil (Diala S4 ZX-I) and a synthetic ester (MIDEL 7131).

A circuit arrangement in compliance with the IEC 60270 was used, which allowed PD measurements, wide-band current measurements and streamer shadowgraphs to be obtained simultaneously. To simulate the quasi-uniform electric fields in transformers, a plane-to-plane electrode system incorporating an adjustable needle protrusion (PNP) was employed. A needle-to-plane electrode system (NP), which is widely used in the field, was also employed to provide reference results.

Based on the PD measurement results, the PD inception fields (PDIFs) of the three liquids were found to be independent of electrode geometry for the investigated tip radius. The PDIF of the synthetic ester is about 13% lower than that of the mineral oil or the GTL oil. Compared with the PD magnitude, the pulse repetition rate is more sensitive to liquid type. At the same voltage under both the NP and PNP configurations, the synthetic ester has the highest pulse repetition rate, followed by the GTL oil, and then the mineral oil.

In divergent electric fields (provided by the NP electrode system), it was found that the streamers in the three liquids have a similar stopping length at the same voltage, even though the apparent charge readings are not the same. The correlations between PD and streamer characteristics indicated that the synthetic ester has the highest branching tendency, and has therefore the smallest stopping length per unit of apparent charge among the three liquids.

In quasi-uniform electric fields (provided by the PNP electrode system), the streamer branching tendencies of the three liquids were largely suppressed. The change from a propagation-induced breakdown in divergent fields to an initiation-induced breakdown in quasi-uniform fields was explained. The correlations between PD and streamer characteristics revealed that the same apparent charge can indicate different levels of streamer development in the insulation, depending on the uniformity of the electric field. Overall, interpreting PD measurement results needs to take the electric field uniformity (PD location) as well as liquid type into consideration.
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I declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
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Chapter 1 Introduction

1.1 Background

Power transformers play an indispensable role in the electrical grid. Their failures, even though rare [1], can pose threats to personal safety, damage nearby facilities, disrupt energy supply and cause potential environmental problems. One typical failure type for power transformers is dielectric failure, which happens when the insulation fails to withstand electrical stress. The source of failure can vary, because large power transformers with high cooling demand have a composite insulation system consisting of insulating liquid, paper and pressboard. When a pressboard suffers from excessive electrical stress, creepage discharges can appear on its surface with permanent marks of carbonisation. When insulating liquid circulates in a power transformer, charges can separate at liquid-paper or liquid-pressboard interfaces and those of negative sign tend to accumulate on pressboards and papers. This can further lead to discharges at the interfaces or across the oil gaps. Insulating liquid can also experience internal discharges [2], especially when the liquid ages and contains many impurities. All these discharge phenomena are called partial discharge (PD).

Depending on the state of matter of the insulation, the discharge processes can be entirely different. In this research, the focus is given to those PDs taking place in transformer liquids. At the initial stage, PDs can be benign as they have not completely bridged the conductors. However, they can cause accumulative deterioration of the insulating liquid over time and eventually become catastrophic. The mechanisms responsible for PD in liquids are so far less understood than in gases or solids. Laboratory investigations into the pre-breakdown phenomena in liquids are often undertaken with high speed camera/video systems so as to observe the development of electrical trees. In liquids, these electrical trees are normally referred to as streamers [3-5]. The physics of
streamers, such as shape, length and velocity, are critical for deducing the possible microscopic processes responsible for breakdown in liquids.

Although both PDs and streamers indicate insulation defects, observing the streamers that appear in a real transformer is infeasible. In industrial practices, the detection of incipient faults mainly relies on PD measurements. PDs can be detected directly through electrical and acoustic means or indirectly through dissolved gas analysis (DGA). During the manufacturing process, the standardised electrical PD measurement, which is detailed in [6], is compulsory in AC withstand voltage tests for high-voltage (HV) facilities. Quality checks may also be carried out using the standard electrical method after transportation, construction and repair. PD activity is usually monitored online by DGA or using UHF (ultra-high frequency) sensors. The rapid development of sensors and of monitoring technologies has contributed to improved reliability and interference immunity. Once alerted by the monitoring system, more comprehensive diagnostics will be performed by engineers to determine whether maintenance or remedial actions are needed. Therefore, both PDs and streamers are concerned with the change in the insulating liquid to a conductive state preceding breakdown, but they have mostly been investigated as two separate topics in past research. The knowledge of the streamer characteristics of liquids can not only offer insights into the breakdown processes, but also assist with the analysis and interpretation of the PD measurement results. This research thus investigates PD and streamer characteristics of transformer liquids as a whole.

Mineral oils, which have been proven to be excellent insulating materials and cooling media in the past century, are still dominant among all types of liquid dielectrics used in oil-filled power transformers [7]. As various types of insulating liquids are now available on the market, mineral oil is no longer the only option. For transformer manufacturers and utilities, considerations for the choice of transformer liquid mainly include electrical performance, cost, viscosity, cooling efficiency, flash point, pour point, water solubility, corrosion resistance, oxidation stability and biodegradability.
With the development in petroleum refining, a new technology called gas-to-liquids (GTL) has been adopted to offer oils with very low sulphur content and highly desirable electrical and thermal performance. GTL based oils are converted from natural gas or gaseous hydrocarbons, and their production is likely to continue to increase [8]. In the past decade, there has also been growing interest in using alternative liquids with less environmental impact and better fire safety. One of the alternatives is synthetic esters [9]. Synthetic esters have superior biodegradability, fire resistance and water tolerance over conventional mineral oils [10] and have been used in 400 kV transmission transformers. Hence, a more thorough understanding of the PD and streamer characteristics of the alternative transformer liquids, i.e. synthetic esters and GTL based oils, is necessary. Three commercial insulating liquids are used in this research, including Gemini X - a conventional mineral oil, Diala S4 ZX-I - a GTL based oil, and MIDEL 7131 - a synthetic ester.

1.2 Motivation and Objectives

Reliable insulation design and early detection of incipient PD faults are crucial to avoiding unexpected transformer failures. They both require a thorough understanding of the PD and streamer characteristics of transformer insulating liquids. This research experimentally investigates the PD and streamer phenomena in liquids under power frequency (50 Hz) AC stress.

The majority of the published studies in the field examine the PD and streamer behaviours of liquids in divergent electric fields, because divergent fields can ease the initiation of PD or streamer and hinder electrical breakdown. Although divergent field conditions are consistent with the PD inception voltage (PDIV) measurement methodology recommended by the IEC (International Electrotechnical Commission) [11], the results obtained under such field conditions more or less lack practical significance since insulating liquids are actually subjected to uniform or quasi-uniform electric fields in power transformers. Considering that it is very challenging to initiate a
discharge in a uniform field and at the same time to prevent breakdown, more measurements should be carried out in quasi-uniform electric fields that PDs and streamers can appear without leading to electrical breakdown. A feasible compromise is to use a plane-to-plane electrode system that incorporates a needle protrusion on the HV plane electrode, as proposed and employed in [12]. With this system, electric fields of different uniformities can be achieved by adjusting the length of the needle protrusion or gap spacing.

In practice, transformer engineers do not have any information about the streamers developing in the insulating liquids. In the decision making process of insulation condition assessment, PD measurement results obtained using conventional electrical means are essential and apparent charge based criteria are most commonly used. PD tests are performed for various transformers where the insulating liquids can have different PD and streamer characteristics. In a specific transformer, discharges can occur at various locations in the liquid where electric field distributions can be different. Adopting a single apparent charge threshold, which has been very often the case in PD testing, may be insufficient. By linking the apparent charge measurements with the characteristics of streamers, the validity of PD magnitude for representing the danger level of discharges in liquids could be checked. The correlations shall ultimately be useful to the interpretation of PD data for more complicated insulation structures. Therefore, more research into conducting PD measurements in parallel with the photographing of streamers in liquids is worthwhile.

From the above considerations, the following objectives are proposed for this research:

- To undertake PD measurements using the conventional electrical means in compliance with the IEC 60270 in both divergent and quasi-uniform AC fields so as to comparatively investigate the PD characteristics of the three liquids;
- To photograph the streamers with the aid of a high-speed video system and comparatively investigate the streamer characteristics of the three liquids in divergent and quasi-uniform AC fields;
- To establish the correlations between PD measurements and streamer physics.
1.3 Thesis Outline

This thesis is divided into seven chapters, with each chapter including a chapter summary. The chapters following this introduction are: a literature review (Chapter 2), descriptions of the experimental setup (Chapter 3), discussions of the experimental results (Chapters 4 to 6), conclusions and further work (Chapter 7).

The literature review in Chapter 2 is divided into two parts, which are PD and streamer. The PD part begins with fundamental concepts of PD and discusses the functionality and limitations of conventional and unconventional PD measurement methods. It then presents the dependence of PD measurements on liquid type, electrode geometry and applied voltage. The streamer part discusses the physics of streamers observed under AC and their dependence on liquid chemistry, electrode geometry and space charge. Part of the results are linked with those obtained under impulse stress.

Chapter 3 describes the circuit arrangement employed in this research and provides detailed specifications of the measuring devices and electrode systems. It includes basic physical and chemical properties of the insulating liquids involved and the preparation procedures of liquids samples. The PD measurement procedures adopted in the experiments are different from those proposed in the IEC 61294. The modifications and benefits are briefly introduced. In addition, the detailed methodology for photographing streamers in insulating liquids is given. As multiple PD and streamer quantities are recorded during the measurements, their definitions are provided. For derived quantities, the calculation methods are provided.

Chapter 4 presents the PD measurement results obtained using the conventional electrical means. Plane-needle-plane and needle-to-plane configurations are used so that the PD characteristics of the insulating liquids are investigated in quasi-uniform as well as divergent electric fields. The PDIVs of the three liquids under various needle-to-plane and plane-needle-plane electrode configurations are first presented. Calculations are performed with COMSOL Multiphysics software to convert the measurements of PDIV
into PDIFs (PD inception field). So the three liquids are compared in terms of not only PDIV but also PDIF. The PD patterns, PD magnitudes and pulse repetition rates of the three liquids obtained at voltages higher than PDIV are discussed for the comparisons of the PD characteristics over a wide voltage range. Their dependence on electrode geometry is also highlighted.

Chapter 5 focuses on the streamer characteristics of the three liquids under divergent field conditions. In divergent electric fields, both positive and negative streamers occur. Differences in their current waveforms are discussed. The stopping lengths, propagation durations and average propagation velocities of streamers are analysed as functions of voltage level, voltage polarity and liquid type. Since measurements of apparent charge and stopping lengths are available in this research, a question is raised about whether apparent charge can adequately represent the danger level of a streamer. To answer the question, correlations between streamer stopping length and apparent charge are established. The different correlations for the three liquids are considered to be related to the degree of streamer branching. Therefore, analysis of streamer areas is presented.

The synthetic ester has a high pulse repetition rate in divergent AC fields, meaning the consecutive streamers can occur within a very short time period. This is advantageous for investigating the space charge effect. By photographing the streamers in the synthetic ester at 45 kV, the effects of homo and hetero space charges on streamer propagation are apparent. The effects are demonstrated in Chapter 5 as the traces of preceding streamers affecting the propagation paths of subsequent streamers.

Chapter 6 deals with the physics of positive streamers in quasi-uniform electric fields. As a result of increasing the uniformity of the electric field, different streamer shapes are recognised in respect of the extent of branching. To support the observations, calculations of streamer area and simulations of the initiation-stage electric field distribution under the two field conditions are performed. Therefore, detailed analysis of the shape change is included in Chapter 6. The changes in the propagation ability of streamers are also reported. Those are linked with the existence of different dominant breakdown factors in
electric fields of different uniformities. Correlations between streamer stopping length and apparent charge are established for the positive streamers in the three liquids in quasi-uniform fields. Through a comparison of the results in Chapter 5 and Chapter 6, the dependence of the correlations on electric field uniformity is discussed. The dependence is also considered to be related to the change in streamer branching behaviour. Implications for industrial practices are provided.

To conclude the three chapters of results and discussions, Chapter 7 recapitulates the critical outcomes of this research and identifies the valuable tasks in the field of PD and streamer characteristics of liquids under AC for future research.
Chapter 2 Literature Review

2.1 PD Fundamentals

2.1.1 PD Phenomenon in Liquids

A partial discharge, by IEC’s definition, is “a localised electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor” [6]. Partial discharges take place in high field regions whose intensity exceeds the withstand limit of the insulating material and these regions are not necessarily adjacent to the conductor, i.e. the source of the electric field. The difference between partial discharge and breakdown is that the former is restricted to a part of the insulating material [13], while the latter refers to the formation of a conducting path that fully connects the electrodes.

The energy exchange during a PD is manifested in many forms, such as current, mechanical wave, electromagnetic wave, chemical reaction, and so forth. PD detection and measurement can be based on any of those phenomena. Various types of discharges exist. Depending on the location, PD can refer to: a) internal discharge occurring in a solid or liquid dielectric, b) surface discharge taking place at an interface constituted by two dielectrics and c) corona discharge occurring in a gaseous dielectric. This research focuses on the PD that takes place in transformer liquids.

Discharges in liquids take place in the gas phase [5, 14-17]. The gas bubbles may already exist prior to the discharges, or appear under electrical stress due to the electrolysis, vaporisation and decomposition of the liquid [13, 18]. The main triggering factors of PD in liquids are electro-dynamic motion, cavitation and movement of conducting particles [19, 20]. In laboratories, PD is usually triggered by the needle electrode in a needle-to-plane or needle-to-sphere electrode system. Under AC stress, the polarity of the voltages
applied across the electrode system changes. Hence, the PD initiated at the needle tip can be positive or negative, depending on the voltage potential of the needle electrode relative to that of the counter electrode.

When the needle electrode acts as an anode, it attracts electrons and repels positive ions. However, electrons gain a greater velocity than positive ions [13, 21]. The electrons that are in contact with the needle electrode are neutralised. Thus, there is a positive space charge region formed by the slower moving positive ions near the needle tip. This positive space charge region weakens the electric field at the needle tip, which hinders the initiation of positive PD [22-24]. In terms of propagation, this positive space charge region acts as an extension of the needle electrode. The electric field at the head of the space charge region is enhanced. When the needle electrode is a cathode, it attracts positive ions and repels electrons. Because of the slow velocity of positive ions, a positive space charge region is formed near the needle tip. This positive space charge region enhances the electric field at the needle tip, and hence eases the initiation of negative PD [23, 25-27]. The electrons dissipate away quickly into the surrounding liquid, probably forming negative ions. These negative space charges, which act as a shielding of the negative tip, weaken the boundary field.

### 2.1.2 PD Equivalent Circuit

Discharges are always first initiated in gas-filled cavities or air bubbles within the liquid, because a cavity is subjected to enhanced field gradients due to its permittivity and shape [13] and it also has a lower dielectric strength than the surrounding liquid. A simplified three-capacitor circuit for mimicking the charging and discharging processes within a liquid is shown in Figure 2-1 [13]. The $V_s$ is the voltage applied across the liquid sample. The capacitance $C_c$ represents the cavity or void. The upper capacitance $C_b$ in series with $C_c$ represents the portion of the liquid that experiences the same electric flux as the cavity or void. The parallel capacitance $C_a$ represents the remaining liquid. The capacitances satisfy the following relationship [13]:

$$C_a \gg C_c \gg C_b.$$  

Equation 2-1
The switch S is closed when $V_c$ reaches the maximum withstand voltage of $C_c$. This allows the current $i_c$ to discharge $C_c$ with a time constant controlled by $R_c$. During the short period of the discharge, the voltage source is considered to be disconnected from the circuit and is therefore incapable of supplying any charges. The voltage across $C_b$ increases as a result of the discharge, indicating that $C_b$ gains charges. The amount of charge that $C_c$ loses is given by

$$
\Delta Q_c = \Delta V_c \cdot \left( C_c + \frac{C_a C_b}{C_a + C_b} \right).
$$

Equation 2-2

With Equation 2-1, this charge can be approximated as

$$
\Delta Q_c = \Delta V_c \cdot (C_c + C_b).
$$

Equation 2-3

$\Delta Q_c$ is the actual amount of charge transferred to the liquid from the site of PD (the gas-filled cavity $C_c$). As the terminals of $C_c$ are inaccessible, this charge quantity cannot be measured. Terminals of $C_a$ can be accessed. This suggests that the voltage drop across $C_a$ can be measured, which is related to $\Delta V_c$ through

$$
\Delta V_c = \Delta V_a - \Delta V_b.
$$

Equation 2-4

During the discharge, we have

$$
\Delta V_b = -\frac{C_a}{C_b} \Delta V_a.
$$

Equation 2-5
By substituting this expression into Equation 2-3, the voltage drop \( \Delta V_a \) becomes
\[
\Delta V_a = \frac{C_b}{C_a + C_b} \cdot \Delta V_c. \tag{Equation 2-6}
\]

\( \Delta V_a \) has a negative sign as \( \Delta V_c \) is negative. Its absolute value is very small since \( C_b \) is much smaller than \( C_a \). Measuring this voltage drop is seemingly feasible. However, the measurement of \( \Delta V_a \) on top of \( V_a \), which can be up to a few hundred kilovolts, requires a sensitivity that is too high to achieve. Hence the voltage drop across \( C_a \) is still not a suitable quantity to be measured.

### 2.1.3 PD Quantities

The most commonly referred quantity of a PD pulse is actually measured using the arrangement depicted in Figure 2-2 [13]. The coupling capacitor \( C_k \) and liquid sample \( C_t \) are charged by the AC voltage source \( V \) before any discharges occur. When \( V_s \) is sufficiently large to trigger a PD in the liquid, a PD current \( i_c \) will appear. As the discharge process only lasts several nanoseconds or microseconds, the voltage source is thought to be isolated from the loop formed by the coupling capacitor \( C_k \) and the liquid \( C_t \). In response to the discharge in \( C_t \), \( C_k \) releases charges to compensate for the voltage drop across \( C_t \). The charge transferred to the liquid is
\[
\Delta Q_t = \Delta V_a \cdot C_t \approx \Delta V_a \cdot (C_a + C_b). \tag{Equation 2-7}
\]
Introducing Equation 2-6, we obtain
\[
\Delta Q_t = \Delta V_c \cdot C_b. \tag{Equation 2-8}
\]
This charge is called the apparent charge. Although the apparent charge is theoretically less than the actual charge transferred from the site of the PD as compared with the \( \Delta Q_c \) in Equation 2-3, it has been the most useful quantity for characterising PD current pulses. The IEC defines the apparent charge of a PD pulse as “a unipolar charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current
pulse itself" [6]. This means that measurements of apparent charge provide information about the increased capacitance of the test object resulting from a PD and the interaction of this increment with the external circuit, instead of revealing the amount of charge locally involved at the site of the PD.

Figure 2-2. Schematic of circuit for measuring apparent charge [13]

Besides apparent charge, there are many other quantities that can be measured or derived to characterise PD current pulses. The definitions of four selected quantities are given below:

- **Pulse number**
  Pulse number is the total number of PD pulses detected in a chosen time interval.

- **Pulse repetition rate**
  Pulse repetition rate is the ratio of pulse number to the duration of the time interval and is often expressed in numbers per minute. If the recording time is set at 1 min, the pulse repetition rate and pulse number will be numerically equal.

- **Phase angle**
  The phase angle of a PD pulse is the phase angle of the applied AC voltage at the time instant when the pulse occurs. It lies in the range of 0° to 360°. Since the applied voltage and PD pulses are both functions of time, they are usually combined into PRPD (phase-resolved partial discharge) patterns.
• Average discharge current

Average discharge current is the sum of absolute magnitudes of partial discharges taking place in a chosen time interval divided by the duration of the time interval. This derived quantity is associated with both the PD magnitude and number of PDs.

The IEC 60270 also defines discharge power and quadratic rate [6]. But these two quantities are not frequently encountered in publications in the field, and therefore are not listed here. The PD inception voltage (PDIV) of an insulating liquid indicates the ability of the liquid to prevent the initiation of partial discharges under electrical stress. The determination of PDIV is normally based on the measurement of apparent charge and it largely depends on the criterion adopted [28, 29]. To enable researchers in the field to carry out PDIV measurements with a standardised test rig and standardised test procedures, the IEC published a technical report (IEC 61294) in 1993 [11]. The report defines the PDIV of a liquid as “the lowest voltage at which a PD of an apparent charge of equal to or exceeding 100 pC occurs” [11] and it recommends the use of a needle-to-sphere electrode system whose gap spacing is 50 mm for carrying out PDIV measurements.

2.2 PD Measurement Methods

There are generally four types of PD measurement methods used in the field, i.e. electrical, acoustic, chemical and optical [30, 31]. The electrical method in compliance with the IEC 60270 is regarded as conventional. In factories, conventional electrical PD measurements are obligatory for HV equipment during AC withstand voltage tests. This section summaries the key requirements for the standard PD electrical measurement. Other electrical methods, including the very-high frequency (VHF) / ultra-high frequency (UHF) methods that are commonly used for on-site PD measurements, are also introduced. The acoustic method and optical method have been used for PD measurements because of their immunity to electromagnetic interference. Dissolved gas analysis (DGA) is a technique for detecting incipient transformer faults including PD.
The use of these unconventional methods for PD measurement is also briefly introduced in this section.

2.2.1 Conventional Electrical Method

The IEC 60270 provides standardised circuit arrangements and specifies the requirements for individual components and digital instruments, thereby allowing engineers and researchers to generate reproducible and comparable measurements from on-site or laboratory tests. The two most fundamental arrangements for detecting and measuring PDs are shown in Figure 2-3 [6], differentiating from each other by the position of the coupling device relative to the test object or coupling capacitor. The two circuits are essentially composed of the model for evaluating apparent charge and a measuring system. The circuit shown in Figure 2-3(b) [6] is more sensitive compared with the one in Figure 2-3(a) [6] since the stray capacitances can add to the coupling capacitor $C_k$ when $C_k$ is closer to the HV side than $C_a$ [13]. But this arrangement at the same time increases the risks of damage to the measuring system when breakdown happens in the test object $C_a$.

Suppressing or eliminating interference is often required in practice, which can be achieved by using the two arrangements included in Figure 2-4 [6] and Figure 2-5 [6]. These two circuits are superior to the basic ones in terms of interference suppression. The so-called balanced circuit arrangement is shown in Figure 2-4 [6]. By adjusting the impedances in the arms, a balanced bridge can be obtained and it cancels common-mode noise between the input terminals of the measuring instrument. In practice, noise elimination is often achieved by replacing the coupling capacitor with a PD-free sample that is similar to the test object.
Figure 2-3. PD test circuits (a) coupling capacitor in series with the coupling device and (b) test object in series with the coupling device [6]

Figure 2-4. Balanced circuit [6]
The polarity discrimination circuit, shown in Figure 2-5 [6], identifies noise signals by examining the polarities of the pulses existing in the two arms. Pulses caused by disturbances within the arms cannot be correlated through their polarities in the measuring instrument. The measuring instrument comprises a specially designed comparator and a selector, by which the unwanted pulses are filtered before they are transmitted for any further processing.

![Figure 2-5. Polarity discrimination circuit [6]](image)

A typical measuring system consists of a coupling device, a connecting cable/optical link and a measuring instrument. The coupling device converts current pulses into voltage signals and rejects power-frequency component and harmonics of the applied voltage. The serial connection of a coupling device with coupling capacitor naturally forms a high-pass filter. The current pulses received by a measuring instrument are further filtered, integrated and processed. In this way, the PD magnitude of a pulse can be quantified and visualised. The external display of a measuring instrument can directly offer a reading of the largest repeatedly occurring PD.

The IEC 60270 classifies measuring instruments into two types depending on their bandwidth: wide-band and narrow-band. A wide-band measuring instrument has a bandwidth in the range of 100 kHz and 900 kHz with its lower limit frequency lying
between 30 kHz and 100 kHz and its upper limit frequency not exceeding 1 MHz [6]. Even though wide-band, such measuring instruments still have a bandwidth narrower than PD pulses. This minimises integration errors. The recommended frequency characteristics of a narrow-band PD measuring instrument by the IEC 60270 are that the tuneable mid-band frequency shall be in the range of 50 kHz to 1 MHz and the bandwidth shall be between 9 kHz and 30 kHz [6]. The narrow-band measurement techniques for the PD detection stem in fact from radio disturbance measurement [13]. Enormous improvements have been brought to the relevant technologies over the past few decades. Nevertheless, the compromise of pulse resolution time for achieving frequency selectability is still an outstanding issue for narrow-band measuring instruments, as the pulse resolution time is proportional to the reciprocal of the bandwidth. The pulse resolution time of a narrow-band instrument is typically greater than 80 µs according to the IEC 60270 [6]. This means that efforts are always needed to eliminate superposition errors during the measurement. So, a narrow-band measuring instrument has a much weaker ability to resolve consecutive pulses of a short duration than a wide-band one.

The use of digital measuring systems for detecting partial discharges is prevalent [32-37]. The key benefit is that the post-processing units can visualise PD pulses in two-dimensional (2D) or three-dimensional (3D) phase-resolved PD patterns. These PD patterns are vitally important as they can assist experienced personnel when deducing the type of defect in the insulation system [38].

### 2.2.2 Unconventional PD Measurement Methods

The conventional electrical PD measurement desires a low-noise environment where PDs induced by insulation defects can be well separated from background noise. This stringent requirement for the measurement environment can hardly be satisfied when the power transformer is in service. Thus, a PD measurement with the conventional method might not be applicable to on-line testing. The complex transformer interior structure and presence of interference increases the difficulty in determining the type and source of a PD when using the conventional method. Furthermore, power transformers in reality
often experience a situation in which multiple PDs occur simultaneously. To overcome the above issues, unconventional methods are needed. Unconventional PD detection methods include the VHF method, the UHF method, the acoustic method, the optical method and DGA.

2.2.2.1 Very-High Frequency (VHF) Method

The VHF method detects electromagnetic transients in the range of 30 MHz to 300 MHz. VHF sensors couple the time-varying magnetic field induced by the discharge current flow. A voltage is then induced in the sensor, which is proportional to the current [39]. Different types of VHF sensors exist, e.g. high-frequency current transformers (HFCTs) and Rogowski coils [39, 40]. Ferrite-cored HFCTs have a good sensitivity to discharge currents, but the sensitivity can be impaired if the core saturates [41]. Air-cored Rogowski coils offer solutions for high current measurements as they do not suffer from core saturation [42]. However, air-cored Rogowski coils generally have a much less sensitivity than ferrite-cored HFCTs [41]. Hybrid VHF sensors are developed by adding air gaps into the ferrite core in a HFCT [41]. They have an improved core saturation level and can achieve a high sensitivity at the same time. Both HFCTs and Rogowski coils provide galvanic isolation. They are non-intrusive and can be fitted to the ground lead during the operation of a power transformer [43].

2.2.2.2 Ultra-High Frequency (UHF) Method

The UHF method detects electromagnetic transients in the frequency band of 300 MHz and 3 GHz. It is initially introduced with the purpose of monitoring GIS (gas-insulated substations). As it demonstrates a strong ability to perform almost instantaneous phase-resolved PD analysis and to detect free conducting particles [44, 45], its application is subsequently extended to power transformers. In power transformers, the rise time and duration of PD pulses are sufficiently short, allowing PD pulse detection in the UHF range [46-51]. The grounded transformer tank provides electromagnetic shielding against external disturbances and thus ensures a good sensitivity to PD for on-site measurement.
UHF sensors can be fitted to oil valves with a straight-through opening or installed into the tank wall. Valve sensors include gate-valve-type, guillotine-valve-type and ball-valve-type [52]. UHF sensors can be installed directly on the tank wall during manufacturing. For commissioned transformers, dielectric windows can be fitted to the flanges on the tank to install plate sensors. Various types of internal and external UHF sensors are available, including disc sensors, cone sensors, loop sensors, field grading sensors, window sensors and pocket sensors. Normally internal sensors have a higher sensitivity than external ones.

The UHF method can have a comparable sensitivity to PD pulses as the conventional electrical method [44]. During on-site testing, this sensitivity can be affected by a range of factors: location of the defect relative to the sensor, transformer geometry, propagation mode of the PD signal, frequency response of the sensor. The propagation of UHF signals inside a power transformer has energy losses for all the three modes of waves – TEM (transverse electric and magnetic), TE (transverse electric) and TM (transverse magnetic). The extent of attenuation primarily depends on the distance between the defect and the sensor. A PD pulse propagating in TEM mode or TE mode attenuates at a rate of 1 dB/km to 2 dB/km [39]. The rate can be increased to 4 dB/km if the PD pulse propagates in TM mode [39]. Refractions, diffractions and reflections at discontinuities along the propagation path are the causes of the attenuation.

The application of the UHF method for detecting and locating PDs in power transformers is very promising. But transformer engineers are facing the issue of the uncertain correlation between the measurements obtained from the conventional electrical and those from the UHF method. The UHF method does not have the charge integration capability. Sensitivity checks of UHF sensors are thus necessary prior to the measurement. A guidance has been proposed by CIGRE for justifying the sensitivity of the UHF method as a diagnostic tool applied to GIS [53]. But no such guidance is available for using the UHF method for power transformers. Trials have been made by some institutes and research organisations to carry out sensitivity checks on power transformers using the same procedures as specified in [53]. Through a series of
laboratory and on-site tests, it has been pointed out that the sensitivity check is indeed able to provide the smallest PD that can be detected by the UHF sensors installed on a transformer [54, 55]. Nevertheless, the correlation between the magnitude of a PD pulse measured in compliance with the IEC 60270 and the amplitude of voltage signal detected by a UHF sensor remains unclear due to the unknown attenuation.

2.2.2.3 Acoustic Method

Another unconventional method that has widely been applied for PD detection in power transformers is the acoustic method. The acoustic method uses ultrasonic transducers to capture the mechanical waves excited by partial discharge activity in the frequency range of 20 kHz to 500 kHz [56, 57]. Ultrasonic transducers can be mounted externally on the transformer tank wall or installed inside the transformer. The advantages of external transducers include the ease of reconfiguration, the flexibility to move to different locations on a transformer or to different transformers, and the retrofitting on existing transformers. However, external transducers are exposed to external noise sources, which is the main disadvantage. Internal transducers detect acoustic signals in the oil and thus provide a good signal-to-noise ratio. However, they cannot be reconfigured or moved. Acoustic systems may incorporate a trigger generated from electrical PD measurement [57]. The electrical trigger initiates the data acquisition of the acoustic sensors when PD occurs and helps to target at the PD activity.

The acoustic method is mostly used to locate PD faults in power transformers [58, 59]. The different arrival times of the acoustic emission at different sensor locations allow the estimation of the different propagation paths. When the acoustic method is used in combination with the electrical method, the time lag of the acoustic signal relative to the trigger signal allows the calculation of the propagation distance. The determination of the PD source location usually assumes that the acoustic signal has a straight-line propagation path. The structure of power transformers is complex and many alternative propagation paths exist, e.g. in metallic transformer tank or pressboards [60]. This poses challenges to the PD locating process. The sonic velocity of transformer liquid varies
with the frequency content of the acoustic signal and oil temperature [61, 62]. The velocity that is typically used for estimating PD location is 1413 m/s [57].

2.2.2.4 Optical Method

The optical method detects ultraviolet (UV) radiation, visible light and infrared (IR) radiation. PD emits weak light as a result of ionisation, excitation and recombination processes [63]. Light emitted from external corona discharges has a wavelength of 280 nm to 405 nm and is mainly in the UV range [63]. It can be measured using UV cameras in direct sunlight. PD in insulating liquids generates light with a wavelength of 350 nm to 700 nm [63], which can be collected by fibre optic cables inside the equipment.

Optical PD detection does not always rely on the light generated by PD. For instance, intrinsic all-fibre interferometers receive coherent light from a laser source, instead of from PD [64, 65]. The laser is transmitted by two separate optic fibres in the interferometer. One fibre is isolated from interferences to carry reference signals; while the other is exposed to PD activity. PD activity changes the transmission characteristics of the fibre by producing a uniform radial pressure [65]. The change of the transmission characteristics causes phase shifts to the laser pulses in the optic fibre that is exposed to PD. When the laser pulses carried by the two fibres recombine, a phase-modulated signal is produced. By demodulating this signal, the original pressure waves produced by PD can be restored and analysed. Another type of fibre optic sensor that is suitable for PD detection in power transformers is extrinsic Fabry–Perot interferometric (EFPI) sensor [66, 67]. EFPI sensors are compact and sensitive [64]. The erroneous polarisation rotation and phase change that may occur in intrinsic all-fibre interferometers become common-mode and uninfluential in EFPI sensors [64, 66].

2.2.2.5 Dissolved Gas Analysis (DGA)

PD in transformer oils can generate hydrogen and acetylene [68-70]. The typical
percentages of hydrogen and acetylene in the total dissolved combustible gases under PD fault are 85% and 13%, respectively [71]. In the case of PD in combined oil and cellulose insulation, carbon oxides can also be formed [72]. These gases can be identified through DGA. The interpretation of DGA measurement results is critical in fault diagnosis. Different methods, e.g. the key gas method, the Rogers Ratio method, the Duval Triangle and the Duval Pentagon, have been proposed for analysing DGA results [70, 73]. Oil type also affects fault gas concentrations and ratios [69, 74]. Thus, much of the ongoing research focuses on the verification of the existing DGA interpretation methods and the development of improved methods for alternative liquids, e.g. esters and GTL based oils [69, 75, 76].

### 2.3 PD Characteristics of Transformer Liquids

Publications in the field deal with many different aspects of PD characteristics, depending on the research aim and measurement method. This review on the PD characteristics of liquids focuses on the results obtained either using a resistor, or through the electrical means in compliance with the IEC 60270. For a single PD event, the pulse amplitude, pulse duration and frequency spectrum can be obtained based on its current waveform. If the voltage is also known, the calculations of charge transfer, discharge power and discharge energy can be performed. Because of the stochastic nature of PD phenomenon, long-duration and repetitive PD measurements are desired for a statistical analysis of the results. For this reason, a PD record usually contains the data measured from a considerable number of PDs that occur over a certain time period and multiple records are usually acquired. A straightforward approach of analysing such large PD data sets is by reproducing them in the form of phase-resolved PD patterns. PD patterns plot the detected PDs as a function of apparent charge, phase, and occurrence frequency and so the distributions of PDs in these dimensions are displayed explicitly. The reproduction of PD patterns and calculations of PD quantities can now be easily achieved by using commercial PD measuring systems. This facilitates data analysis and fault diagnosis.
2.3.1 PD Current Pulse

Under AC stress, PDs of both polarities can appear. Positive PDs appear in positive half cycles of the applied voltage and negative ones in negative half cycles. An example of the typical waveform of a positive PD current pulse in liquids is shown in Figure 2-6 [77]. The current signal contains high-frequency oscillations that are superimposed on a lower frequency positive pulse. The degree of high frequency fluctuation is less in the case of gases [77]. The pulse duration is in the range of a few to a few tens of microseconds and the amplitude is of a few milliamperes. In a standard PD measurement circuit, the PD pulse is shaped and fed to the PD instrument, and thereby its apparent charge value can be computed and is often expressed in picocoulomb (pC). At the location where the PD current is produced, the insulation has proven to be conductive, as the theoretical calculations of the current generated by a moving conductive cylinder agree with the measurements obtained under impulse stress [78]. However, the current pulse still causes a voltage drop across the conductive channel.

![Figure 2-6. Typical waveform of positive PD (needle-to-plane electrode configuration, needle tip radius = 10 µm, gap spacing = 30 mm, applied voltage = 30 kVrms) [77]](image)

Unlike positive PDs, negative ones appear in liquids as pulse bursts [79-86]. They are formed of consecutive PD pulses and each group of pulses results from an originally initiated pulse triggering a sequence of pulses. A pulse burst generally consists of pulses of ascending magnitudes and increasing separation times [82], as illustrated in Figure 2-7.
The two key attributes characterising a pulse burst are the average time duration between two adjacent pulses in the burst and the charge transferred by individual pulses. However, the pattern of pulse burst could be random [82], which is disadvantageous for recognising the charge transfer during the development of the PD.

Figure 2-7. Typical negative pulse burst of a mineral oil in a divergent field with the apparent charge measured by a narrow-band detector (needle-to-plane electrode configuration, needle tip radius = 20 µm, gap spacing = 30 mm, applied voltage = 32 kVrms; upper trace: pulse burst, 10 mV/div; lower trace: response of a 300 kHz PD detector to the pulse burst, 100 mV/div; oscililoscope bandwidth: 500 MHz, abscissa: 1 µs/div; the total charge transfer of the pulse burst, 44.0 pC, is measured by the narrow-band PD detector; the proportion of charge carried by individual pulses is calculated based on the pulse magnitude and is indicated in the upper trace) [82]

The waveform of pulse burst also varies with liquid type due to different electron affinities and boiling points [80]. This understanding is based on the fact that gas bubbles exist at the needle tip during the discharges [5, 17, 87-89], because the electron affinity and boiling point of a liquid can affect the tendency of vapour generation and the ability to sustain the discharges in the vapour region. In other words, the easier a liquid can be ionised and vaporised, the more likely bursts of pulses will occur.
2.3.2 PD Pattern

Digital PD measuring systems provide measurements of apparent charge, phase angle and PD occurrence number/frequency within a certain detection period and are able to present these data in PD patterns. Some early investigations in the field plot the number of PDs as a function of PD amplitude. Such plots provide information of the PDAD (PD amplitude distribution) of an insulating liquid. By comparing the PDADs obtained at different voltages, the PD behaviour of an insulating liquid can be fingerprinted [90-92] and the calculation of PDIV is feasible. The range of PD amplitude in a PDAD extends as the applied voltage increases, because PDs of a greater amplitude can occur [90-93].

Nowadays, the most commonly used PD patterns in PD measurements are phase-resolved PD (PRPD) patterns. PRPD patterns provide a straightforward inspection of the magnitude and phase angle distribution of discharges, while masking information about their time-domain relations. In 2D PRPD patterns (Φ-Q PD patterns), the magnitudes of PDs are plotted as a function of phase angle. In 3D PRPD patterns (Φ-Q-N PD patterns), the magnitudes of PDs are plotted as a function of phase angle and discharge number. A typical 2D PRPD pattern of hexadecane is depicted in Figure 2-8 [94]. The PDs in both positive and negative half cycles of the applied voltage have a ‘mountain’ shape. This is because PDs that are greater in apparent charge are fewer in number. Generally, the PD magnitude and number of PDs read from PD patterns are expected to increase if the field intensity is increased, as shown in Figure 2-9 [95] and Figure 2-10 [95].

The positive and negative discharges in a PD pattern are asymmetrical. Under divergent AC stress, positive discharges are normally larger in PD magnitude than negative ones [96], since a negative PD current comprises short-duration pulses without an obvious DC component. In much of the research that employs needle-to-plane or needle-to-sphere electrode systems, the PD magnitude of a liquid at a certain voltage is linked to the largest positive PD. Positive discharges are larger but not necessarily more frequent than negative discharges. Based on the literature, the voltage polarity that gives more discharges is associated with liquid type, tip radius of needle electrode and measuring system sensitivity [28, 97, 98]. When evaluating the overall degradation effect of
discharges, the total number of PDs is representative. However, when looking into the mechanisms of PD occurrence under each polarity, separate counts become more useful. Similar to the PD magnitude and number of PDs, the phase angle range in which PDs occur changes with applied voltage. PDs occur in a wider phase angle range as the voltage increases [99].

![Figure 2-8](image1.png) ![Figure 2-8](image2.png)

**Figure 2-8.** PD pattern of hexadecane with aromatic additives: (a) positive PDs and (b) negative PDs (needle-to-plane electrode configuration, needle tip radius = 20 µm, gap spacing = 10 mm, applied voltage = 30 kVrms; PD detector: Doble Lemke LDS-6) [94]

Different transformer liquids can have different PD magnitudes, pulse repetition rates or phase distributions of the discharges. From Figure 2-9 [95], the ester liquids have a larger PD magnitude than the mineral oil when the applied voltage is the same. This is particularly obvious at 70 kV, where the PD magnitude of the synthetic ester is about 6800 pC and that of the mineral oil is about 2800 pC. According to Figure 2-10 [95], the ester liquids also have a larger pulse repetition rate than the mineral oil when the applied voltage is the same. The differences can exist in either positive or negative half cycles of the applied voltage or both [95, 100]. Therefore, PD patterns normally vary from liquid to liquid. The PD pattern of a transformer liquid varies with the selection of electrode geometry. According to [101] and [102], PD magnitude decreases with increasing gap spacing at the same voltage because of the reduction of the tip field. It is reported in [29, 103, 104] that higher PDIV measurements are recorded as a result of an increased gap spacing. This can be attributed to the same electrode geometry dependence of PD magnitude. An increase in the gap spacing leads to a reduced number of PDs [105].
other words, increasing the gap spacing without changing the applied voltage lowers the tip field. When the same liquid is tested with different electrode configurations, the configurations providing a higher electric field at the needle tip generally result in a larger PD magnitude and number of PDs. The phase angle range of discharges is also dependent on electrode geometry [94, 105]. With increasing gap distance, or reduced electric field, PDs occurs in a narrower range of phase angle [105].

![Graph showing maximum PD amplitudes of transformer liquids as a function of applied voltage.](image)

Figure 2-9. Maximum PD amplitudes of transformer liquids as a function of applied voltage (electrode configuration: needle-to-sphere; needle tip radius = 3 µm, needle length = 25 mm, gap spacing = 50 mm, sphere diameter = 12.5 mm; maximum PD amplitude equals the largest apparent charge recorded in the PD pattern; recording duration = 1 minute; PD detector: LEMKE LDS-6) [95]

Much of the published work concerning the PD characteristics of liquids used needles with a tip radius between 1 and 50 µm and set the gap in the range of 5 to 50 mm. These configurations can provide such divergent electric fields that PD occurrence is facilitated while breakdown is hindered. Although the PD characteristics of liquids in uniform electric fields are more sensitive to the presence of contaminants, simulating the actual field conditions is not feasible for laboratory PD measurements in that any PD initiated can instantly result in breakdown. A compromise is to use quasi-uniform electric fields, which can be achieved by placing a plane electrode behind the needle tip to enhance field
homogeneity [12]. This enables the PD behaviour of a liquid to be closer to reality and guarantees a certain gap between PDIV and BDV (breakdown voltage) and therefore PD measurements can still be carried out. So far, quasi-uniform electric fields have been used in optical studies of streamer physics [12, 106], but have barely been used in the examination of PD characteristics of transformer liquids.

Figure 2-10. Pulse repetition rates of transformer liquids as a function of applied voltage (electrode configuration: needle-to-sphere; needle tip radius = 3 μm, needle length = 25 mm, gap spacing = 50 mm, sphere diameter = 12.5 mm; recording duration = 1 minute; PD detector: LEMKE LDS-6) [95]

2.4 Streamer Characteristics of Transformer Liquids

Although both PD and streamer characteristics can be used to describe the ability of a liquid to remain insulated under electrical stress, the former focuses on the charge transfer between the liquid and an external circuit, while the latter focuses on the physics of the conductive channels formed in the liquid. Investigations into streamer phenomena have contributed to a knowledge base for understanding the breakdown mechanisms. This section provides a brief overview of the experimental findings of streamers and the
theories and hypotheses that have been proposed which go some way to explaining how streamers develop in liquids, with the focus given to streamer behaviours under AC stress.

Streamers in this thesis stand for all types of temporal disturbances developed in a liquid before breakdown, which are distinguished from streamers in gases. The development of a streamer in a liquid incorporates gaseous and electronic processes. Early discussions on the possibility of the formation of a gaseous region in liquids as a result of energy injection can be traced back to Lewis, Watson and Sharbaugh’s work [107, 108]. Centred on the observation of a gas bubble, the streamer theory was established in 1966 [3], and has been widely accepted as the framework for studies on the breakdown and pre-breakdown phenomena in insulating liquids. It suggests that the nature of streamers is a low-density gaseous channel where breakdown mechanisms are analogous to those for gases. Many other published papers have confirmed the existence of gas bubbles in liquids during discharge by showing the effects of hydrostatic pressure on streamer formation [5, 14-17, 87-89]. Electronic processes also exist, as electron-releasing and electron-trapping additives can effectively change the streamer characteristics of liquids [109-112].

Streamers can be classified as positive or negative, based on the polarity of the electrode from which they emanate. Streamers can be either ‘bushy’ or ‘filamentary’. An example of the filamentary streamer is given in Figure 2-11 [113]. The development of streamers consists of two stages – initiation and propagation. As at both stages there are pressure or density variations in the liquid, the consequent refractive index of the gaseous region that differs from that of the surrounding liquid enables streamers to be visualised by means of Schlieren or Shadowgraph techniques [114-120]. Streamers propagating at high velocities can be directly photographed using high-speed camera/video systems as their light emission is strong.
2.4.1 Streamer Initiation

The occurrence of negative streamers is always accompanied by a fast current burst and the formation of a microbubble attached to the cathode, as shown in Figure 2-12 [4]. The sequence of the appearances of the current and bubble were subject to debate until Lesaint and Tobazéon published their experimental results. It turns out that the current pulse appeared before the bubble [4, 5]. The merit of this finding is that it discloses the starting point for the interactions between gaseous and electronic processes. This finding also supports the calculations made in [3], arguing that a bubble whose diameter is several micrometres can be produced if vaporising the liquid is highly efficient in converting the energy carried by the current. Hence, electrons emitted from the cathode are able to ionise and vaporise liquid molecules and create a gas-filled cavity [120, 121], being the initiation process for negative streamers.

The formation of bubbles also accounts for the initiation of positive streamers. As a result of the erratic occurrence of bubbles and the rapid establishment of the gaseous channel when the point electrode is anode [122], little photographic evidence is available. The model for positive streamer initiation is shown in Figure 2-13 [120]. In the model, the strong electric field pulls negative charges towards the tip. As a result, some of the negative charges are neutralised when in contact with the tip, and the rest stay between the tip and a region of net positive charge. Since this process leads to heating, dissociation and ionisation of the liquid near the tip [120], it produces a conductive
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gaseous region [123].

Figure 2-12. Bubble generation near a sharp tip in a paraffinic transformer oil (tip radius = 3 µm; applied voltage = 16 kV; this is a modified image, the original image is published in [4])

Figure 2-13. Charge distribution near the point anode [120]

Measurements of streamer inception voltage/field can be affected by the definition used; therefore comparisons of inception threshold are valid only when the same criterion is adopted. When comparing the streamer inception voltage/fields in different liquids or under different experimental environments, the streamer number based criterion is the most common; for example, streamer inception voltage is the voltage at which streamers appear at a rate of 10/min. In divergent AC fields, streamers first appear near crest voltages and negative streamers start to appear at a lower voltage than positive ones [4]. Having obtained measurements of inception voltage, calculation of streamer inception
field is possible. For needle-to-plane electrode systems, reasonably good estimates of streamer inception field can be obtained using Mason’s equation [124]:

\[ E_{\text{max}} = \frac{2U}{r \ln \left(1 + \frac{4d}{r}\right)} \]  

Equation 2-9

where \( U \) is the instantaneous voltage applied across the electrodes, \( r \) is the radius of the point electrode and \( d \) is the gap spacing. The calculation assumes that the needle tip can be represented by a hyperboloid and it is only valid when \( d > 10r \) [124]. The accuracy of the calculation is more sensitive to the applied voltage and tip radius than to the gap spacing [124]. For more complicated electrode systems, the inception field can be obtained using FEM (finite element method) with the aid of commercial modelling and calculation tools. Without taking into consideration the effects of space charge, the streamer inception field of a liquid may vary widely from a few tens of kV/mm to more than 1000 kV/mm because it increases as the tip radius decreases under AC, as shown in Figure 2-14 [125].

In moderately divergent fields (obtained with a tip radius of larger than 500 µm), the streamer inception field is higher under impulse than under AC [125]. The reason is that AC voltages have longer durations than impulse voltages, thereby having a larger probability of triggering a streamer at the same voltage level. The measured streamer inception voltage based on the same occurrence frequency will give a lower voltage under AC than under impulse. The space charge effect becomes more influential as the tip radius decreases. According to the results depicted in Figure 2-14 [125], the streamer inception field becomes higher under AC than under impulse in divergent fields (obtained with a tip radius smaller than 50 µm). Moreover, since AC voltages have a longer duration than impulse voltages, charge injection is more intense under AC than under impulse. Space charge is therefore more detrimental under AC in terms of its influence on field distortion.
Both positive and negative streamers can appear with a ‘bushy’ or ‘filamentary’ shape, depending on the electrode geometry and applied voltage. The inception voltage of ‘bushy’ positive streamers is particularly sensitive to tip radius as it needs highly divergent electric field conditions. When the tip radius exceeds a critical value, ‘bushy’ positive streamers do not occur and only ‘filamentary’ streamers can be observed. Depending on the electrode system, the critical tip radius varies in the range of 3 µm to 6 µm [89, 126, 127]. Under impulse stress, a field of 600 kV/mm to 1000 kV/mm is needed to trigger ‘bushy’ positive streamers, and less than 600 kV/mm for ‘filamentary’ streamers [126]. Considering that these field intensities belong to the region II in Figure 2-14 [125], one should expect the values to increase in the case of AC stress. Literature values of streamer inception field are more or less overestimated as the field attenuation caused by homo-charge is in most cases neglected. Positive streamers initiated are likely to be ‘filamentary’. Negative streamers initiated in divergent AC fields are likely to be ‘bushy’. But with increasing stress or field uniformity, these negative streamers can change to the same ‘filamentary’ look as positive ones.

The variations of streamer inception voltage with changing electrode geometry can be predicted when the liquid chemistry is the same. Electrode geometry can be altered in three ways, including changing the gap spacing, changing the size and shape of
electrodes and changing the connection points to voltage source and ground. All three ways alter the electrostatic couplings among the electrodes, liquid and surroundings. Streamer inception voltage falls with the increasing sharpness of the HV electrode, the increasing size of ground electrode and the decreasing gap spacing between the electrodes. If the electrode geometry is asymmetrical, the streamer inception voltage is also lower when the sharper electrode is connected to the HV side. The electrode geometry dependence of streamer inception voltage is verified by the experiments documented in [128].

The addition of cellulose particles can also reduce the streamer inception voltage [125, 129] and the effect is more profound in uniform fields than in divergent fields [125]. This could be attributed to two reasons. First, contaminants in the liquid are weak points, for which breakdown voltage measurements decrease as a result of contamination [130, 131]. In uniform or quasi-uniform fields, electrodes can be less influential than contaminants in determining the electrical strength of a liquid. When an electric field becomes more divergent, electrodes play a more significant role in triggering streamer or breakdown, outweighing the effects of contaminants. In addition, the determination of streamer inception voltage, as previously mentioned, can be affected statistically by streamer frequency. Increasing cellulose particle contents can lead to an increased streamer frequency [129], being the second cause of the reduced inception voltage. The effect of cellulose particles on streamer inception may have a limit, above which a further increase in particle concentration cannot reduce streamer inception voltage.

2.4.2 Streamer Propagation

2.4.2.1 Propagation of negative streamers

Propagation of a streamer refers to growth or elongation. It thus should not be misunderstood as detachment from an electrode or travelling between the electrodes. For a negative streamer, the electrons emitted from the cathode move along the surface of the cavity to the point furthest away from the cathode, resulting in a potential on the surface approximately equal to that of the cathode [132]. If sufficient energy is injected for
ionising and heating the liquid, the streamer will propagate and branch and the current pulses will maintain the equipotential with the cathode. If the discharges in the cavity cannot be sustained, the negative streamer will detach from the cathode and vanish [133].

The propagation behaviour of a streamer under AC mainly relies on the mean field intensity, which is calculated from the applied voltage divided by the gap spacing [26]. Unlike the tip field that determines whether streamers can be initiated, the mean field is not a function of tip radius. The ratio of the tip field to the mean field characterises the non-homogeneity of the electric field. In divergent fields, streamers can appear at low voltages but the mean field may be too low for the streamers to propagate. In uniform fields, streamer initiation needs very high voltages and all the streamers initiated can propagate due to the high mean field. The minimum mean field for a negative streamer to propagate is approximately 4 kV/mm. Negative streamers that appear in a field under this threshold will detach from the cathode at a velocity of 10 m/s and dissipate into the liquid. If the mean field is between 4 and 8 kV/mm, negative streamers can propagate but they may cease growing at a certain point. Above 8 kV/mm, all the negative streamers initiated are able to reach the ground electrode and trigger breakdown [4].

Negative streamers in ‘bushy’ shape propagate at a velocity of 0.3 mm/µs. Current bursts occur along with these streamers and they are formed with discrete pulses, as previously depicted in Figure 2-7 [82]. The pulse bursts create an energy density of about $10^{-3}$ J/mm$^3$ for vaporisation processes [4]. At higher voltages, ‘filamentary’ negative streamers occur with a propagation velocity of up to 2 mm/µs [26]. The current injection is still in the form of pulse bursts. Unlike under impulse stress, streamer propagation velocity under AC is not as important as streamer length. In Figure 2-15 [128], negative streamers propagate nearer than positive ones in divergent AC fields when the same voltage is applied [26]. For this reason, they are considered less dangerous and have attracted much less research than positive streamers.
At propagation stage, the frequency of negative streamer occurrence in AC fields increases exponentially with applied voltage [4] and the increasing rate reduces above a critical point [125], as shown in Figure 2-16 [125]. The addition of cellulose particles can neither increase streamer frequency nor streamer length in divergent fields under negative polarity [26, 125]. So, liquid condition plays a negligible role in the propagation of negative streamers in divergent AC fields. In more uniform electric fields, streamer frequency can increase as a result of particle contamination at the propagation stage [125]. This, together with the lowering effect of particle contamination on inception field threshold, can cause a lower breakdown voltage. Because of the higher mean field threshold for propagation, negative streamer propagation can be more sensitive to electrode geometry than a positive one. With a large gap spacing of 350 mm, changing electrode configuration from rod-to-plane to sphere-to-plane with a triggering wire is able to suppress negative streamer propagation in the tested voltage range [26].
2.4.2.2 Propagation of positive streamers

Similar to that of negative streamers, a certain mean field is required to allow a positive streamer to propagate under AC. As for positive streamers, electrons are pulled away from cations to maintain a sufficient streamer tip field. For the 10 µm filament shown in Figure 2-13 [120], the theoretical estimate of the minimum tip charge is 3 to 4 pC for sustaining the high-field extraction of electrons at the streamer tip [120]. This critical charge value is calculated by equating the Coulombic field at the edge of the streamer tip (at a distance of 5 µm from the centre of the streamer tip) with the Laplacian field that initiates the streamer growth at the needle tip [134]. The measured charge transfers using a capacitor in series with the test sample conform to the estimation [135]. The mean field threshold for the propagation of positive streamers is about 3.5 kV/mm under AC [4, 136], which is lower than the 4 kV/mm threshold for negative streamers. There are thus three regions, where the causes of breakdown are different. When the mean field is lower than 4 kV/mm, i.e. in divergent fields, breakdown is mainly governed by streamer propagation. Under this condition, positive streamers are much more likely to cause breakdown than negative ones due to their stronger ability to propagate. When the mean
field is higher than 8 kV/mm, i.e. in moderately divergent fields or uniform fields, the field favours streamer propagation and breakdown is mainly governed by streamer initiation. Negative streamers can appear at a lower voltage than positive ones, and are therefore more likely to cause breakdown under such field conditions. In the intermediate region where the mean field is between 4 and 8 kV/mm, streamers of both polarities can trigger breakdown.

Depending on the propagation velocity, positive streamers can be characterised into 4 different modes, as shown in Figure 2-17 [137]. Two of them have been observed under AC, which are the 1st and 2nd modes. The other two modes need overvoltages far exceeding the breakdown voltage. They are, therefore, mainly investigated under impulse stress. Positive streamers that propagate in 1st mode under AC have a velocity of under 1 mm/µs. These streamers are ‘bushy’ in shape and their current consists of pulses of short pulse width. Therefore ‘bushy’ positive and negative streamers have very similar characteristics. The light emission is in most cases too low to be differentiated from noise. Similar to ‘bushy’ negative streamers, 1st mode positive streamers can be generated in highly divergent fields but they hardly propagate. Generally, ‘bushy’ streamers can rarely cause breakdown.

By increasing the applied voltage, positive streamers can shift from 1st mode to 2nd mode. 2nd mode positive streamers have a ‘filamentary’ shape. Their currents contain not only rapid pulses but also a DC component, as previously presented in Figure 2-6 [77]. The light emission is also stronger. Under AC stress, 2nd mode positive streamers are dominant and their propagation velocity ranges 1 to 3 mm/µs [4, 26, 128]. The velocity is independent of the applied voltage for the same liquid and remains constant during the streamer propagation [4, 128, 138]. The current understanding of this phenomenon is that the rate of ionisation at the streamer tip is related to streamer propagation velocity. An increase in the streamer propagation velocity, for example, indicates a higher rate of ionisation, which requires a higher current to be injected. The increase in the current flow can cause a greater voltage drop along the streamer, thereby reducing the tip field and maintaining a stable rate of ionisation [4].
Figure 2-17. Typical photographs of positive streamers in mineral oil: (A) 1\textsuperscript{st} mode, (B) 2\textsuperscript{nd} mode, (C) 2\textsuperscript{nd} mode, (D) 3\textsuperscript{rd} + 2\textsuperscript{nd} modes and (E) 4\textsuperscript{th} mode [137]

The propagation behaviour of 2\textsuperscript{nd} mode positive streamers has been investigated using various electrode systems, with gap spacing ranging from 5 mm to 800 mm [4, 26, 128]. By adjusting the configuration and dimension of electrodes, the dependence of positive streamer propagation on electric field distribution as well as applied voltage has been examined. If the electrode system is fixed, the curve of stopping length against applied voltage (L-V curve) is approximately linear until the breakdown limit is approached. For a gap spacing of less than 250 mm, the voltage required to elongate positive streamers by 10 mm should be in the range of 20 kV to 85 kV [4, 128]. In gaps larger than 250 mm, streamer tips can be far away from the HV electrode. Therefore, the propagation of positive streamers is mainly determined by the field at the streamer tip and is less dependent on electrode geometry [26]. For the same reason, in large gaps under divergent field conditions, the effect of cellulose particles on positive streamer propagation is negligible [26], as shown in Figure 2-18 [26].

In Figure 2-19(a) [139], the L-V curves obtained in the 50 mm gap under AC and impulse stress are almost identical. In the 200 mm gap, as can be seen from Figure 2-19(b) [139], the two curves separate at above 180 kV after the L-V curve under AC deviates from the linear trend. So, AC field conditions can favour positive streamer propagation in large oil gaps.
Figure 2-18. Stopping lengths of positive streamers as a function of applied voltage in sphere-to-plane electrode geometries incorporating a triggering wire (gap spacing = 300 mm, wire length is between 5 and 10 mm, wire diameter = 0.1 mm) [26]

The occurrence frequency of positive streamers increases in a very similar way to that of negative ones when voltage increases. In divergent AC fields, positive streamers are always fewer than negative streamers at the same voltage [4]. However, when the electric field becomes less divergent, the number of positive streamers may exceed that of negative ones, which is illustrated by Figure 2-20 [125].
2.4.3 Space Charge Effect

Although AC voltages in experiments pose challenges in predicting streamer occurrences and synchronising the measuring system, they also provide opportunities for examining the interactions between streamer behaviour and charge distribution. This is because streamer initiation and propagation under AC is more liable to be influenced by space charge than under impulse due to polarity alternation, continuous charge supply [140] and sufficient time for forming space charge [141, 142]. In a dielectric liquid, both ionic dissociation and molecular ionisation can produce cations to form positive charges [143]. Negative charges are primarily formed by electrons since their high mobility allows rapid separation from cations. The sources of electrons include direction injection when the needle tip acts as a cathode as well as ionisation process. Under AC, occurrences of streamers can be very close in time. An early streamer can leave residual charges in the liquid. Governed by the electrical field, the charges move and partially recombine with the molecules and ions present in the liquid. The rest are regarded as space charge, which alters the electric field distribution [144] and affects the initiation and propagation of subsequent streamers. This is known as the space charge effect.

Figure 2-20. Inception frequency of negative and positive streamers with different needle/rod sizes (open symbol: negative, full symbol: positive, needle-to-plane or rod-to-plane electrode geometries at a gap spacing of 40 cm) [125]
Space charge can be either homo or hetero, depending on its polarity relative to that of the needle tip. Homo space charge has the same sign as the needle tip, which happens when consecutive streamers in the same cycle (voltage polarity does not alter). In contrast, the sign of hetero space charge is opposite to that of the needle tip. This indicates that the subsequent streamers are in the opposite polarity as the preceding ones. So hetero space charge is present after the polarity of the applied voltage reverses.

A lowering of the tip field will occur if homo space charge is in the vicinity of the needle tip, which hinders streamer initiation [22-24] and results in an increased inception voltage [24]. Unlike homo space charge, hetero space charge can enhance the local field near the needle tip [23, 25-27]. This can result in lower streamer inception voltage measurements and higher streamer length measurements. An exceptional finding is identified in [24], where positive space charge is able to increase the inception voltage of negative streamers. A possible explanation is that positive space charge enhances the electric field at the cathode tip; it may at the same time lower the availability of electrons. The competition of the two factors may be affected by space charge density, electrode geometry [142] and applied voltage and only one dominates. This is analogous to the electron trapping effect of iodine in a transformer oil argued in [23]. The paper shows that low concentrations of electron scavengers reduce the streamer velocity due to limited availability of electrons near the anode. High concentrations of electron scavengers, instead of further reducing the streamer velocity, increase the streamer velocity as a result of field enhancement at the anode. Hence, field distortion is the major focus when analysing the space charge effect. But attention should also be paid to the factors that may affect the electronic processes.

2.5 Summary

This chapter introduces conventional and unconventional PD measurement methods and discusses the working principles of unconventional methods. It presents the PD
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characteristics of liquids and their dependence on liquid type, electrode geometry, and applied voltage by discussing the published results obtained from the conventional method.

The conductive nature of streamers is an important aspect of the investigations on pre-breakdown phenomena in liquids. So this chapter also deals with the initiation and propagation processes of streamers in liquids. It is found that streamer initiation dominates breakdown in uniform electric fields, whereas streamer propagation dominates breakdown in divergent electric fields. The transition between the two scenarios, which is the streamer behaviour under quasi-uniform field conditions, has only been investigated under impulse stress. Considering that the results are potentially of great use for understating field testing data, more experiments are desired in quasi-uniform AC fields. One key difference between AC voltages and impulse voltages is that different degrees of space charge effect take place. The field distortion can be caused by either homo or hetero charge, depending on the sign of the space charge relative to that of the needle electrode. Up to now, there has been little research into the space charge effect using insulating liquids as test objects, and hardly any research undertaken using insulating liquids under AC stress. The existence of space charge has posed considerable challenges in modelling the formation of streamers and the interactions between streamers and the applied field. The space charge effect in liquids under AC thus also needs more research.
Chapter 3 Experimental Description

This chapter first introduces the experimental setup used in this PhD study for investigating PD quantities, streamer physics and PD current pulses. It then describes the dimensions of the electrode systems, sensitivity of the measuring system and specifications of the high speed video system. The key properties of the transformer liquids are provided, along with the treatment procedures for preparing liquid samples. The last section of this chapter details the procedures for carrying out PD measurements and wide-band current measurements and for photographing streamers. Synchronisation mechanisms are detailed. Since the result analysis covers a series of derived quantities, examples of data processing are given.

3.1 Experimental Setup

3.1.1 Test Circuit

The circuit arrangement adopted for this research complies with the IEC 60270 and its schematic is depicted in Figure 3-1. The primary components include a variable single-phase AC source, a step-up transformer, a coupling capacitor, a measuring impedance, a commercial PD detector, a test cell, oscilloscopes and a capacitive voltage divider. For photographing streamers, a high-speed video system is also used along with a light source. Power-frequency (50 Hz) AC voltages (the voltages presented in Chapters 3 to 6 are rms values) are applied. Constrained by the capacity of the voltage divider formed by $Z_1$ and $Z_2$ ($Z_1 : Z_2 = 10000 : 1$), the maximum of the applied voltage across the test cell is 70 kV. The circuit also comprises an overcurrent relay and a current-limiting water resistor to prevent damage to the power supply in case of breakdown.
Chapter 3 Experimental Description

**Figure 3-1.** Experimental setup for photographing streamers in parallel with wide-band current measurements and PD measurements

PD current pulses flow between the capacitor and the test cell through the measuring impedance and 50 Ω series resistor. 50 Ω coaxial cables are used for impedance matching purposes. The PD detector and Oscilloscope 1 receive voltage signals converted by the measuring impedance and resistor, respectively. When no needle is inserted into the HV electrode, the noise of the complete setup is no more than 12 pC at 55 kV, which is the highest voltage level used in the measurements.

### 3.1.2 Electrode Configurations

The electrode systems are fitted in a transparent test cell that contains 1.4 L of liquid samples. The container is made of PERSPEX. Referring to Figure 3-2, two electrode systems are employed, including a needle-to-plane (NP) electrode system and a plane-needle-plane (PNP) electrode system. The PNP electrode system is essentially a plane-to-plane electrode system that incorporates a needle protrusion in the centre. The plane electrode on the HV side acts as a needle holder that can reduce the electric field at the needle tip when the needle protrusion is short. Depending on the length of the needle protrusion relative to the distance between the two plane electrodes, electric fields of various uniformities can be achieved. In the experiments, the liquid samples are tested under divergent and quasi-uniform field conditions.
For both systems, gap spacing is defined as the distance from the needle tip to the
grounded plane electrode. This means that for PNP configurations, the sum of the gap
spacing and needle length is equal to the plane-to-plane distance. The diameter of the
plane electrodes is 50 mm. The thickness of the plane electrodes is 10 mm. The
electrodes are made of brass. Stainless steel needles are used as point electrodes and the
needle electrodes used in the experiment have a tip radius of 3 µm. The tip radius of the
needle electrodes is examined using Carl Zeiss Axio Imager M1m microscope [95].
Quality check was performed after the test cell was constructed to ensure the plane
electrodes are parallel. Gap spacing is controlled by adjusting the brass rods holding the
electrodes and checked by using thickness gauges.

The results that will be presented in Chapter 4 are obtained with various gap spacings
and needle lengths as the purpose is to examine the electrode geometry dependence of
PD characteristics. The results that will be presented in Chapters 5 and 6 are obtained
with the NP and PNP electrode configurations at a fixed gap spacing of 40 mm. As for
the PNP configuration, the needle length is fixed at 10 mm (total plane-to-plane distance
is 50 mm).

### 3.1.3 PD Detector

A computer-aided PD detector, LEMKE LDS-6, is used. Its performance meets the
requirements of the IEC 60270 and the key electrical specifications are listed in Table
3-1. The methodology for undertaking PD measurements is detailed in Section 3.3.1.
Table 3-1. Electrical specifications of LDS-6 [145]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower frequency limit</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Upper frequency limit</td>
<td>1000 kHz</td>
</tr>
<tr>
<td>Minimum detectable apparent charge</td>
<td>&lt; 1 pC</td>
</tr>
<tr>
<td>Single pulse resolution capability</td>
<td>up to 100 kHz repetition rate</td>
</tr>
<tr>
<td>Pulse resolution time</td>
<td>10 µs</td>
</tr>
<tr>
<td>Pulse polarity recognition</td>
<td>1 pC</td>
</tr>
</tbody>
</table>

3.1.4 High Speed Video System and Oscilloscopes

Streamers that occur in the liquids are photographed by a high speed video system. The high speed video operates at a frame rate of 20,000 fps. At this frame rate, the pixel resolution of the high speed video is 704*520 (366,080 pixels). The Shadowgraph technique is adopted, so the test cell is located between the high speed video and the light source. Streamer shadowgraphs obtained are in fact the 2D projections of the real 3D structures. The PD currents accompanying the formation of streamers are recorded by Oscilloscope 1 (LeCroy WaveJet 314A, whose bandwidth and sampling rate are 100 MHz and 1GS/s, respectively). Oscilloscope 2 (Agilent MSO8104A) functions as a trigger unit by sending 5V TTL (transistor-transistor logic) trigger signals to the high speed video system and Oscilloscope 1. The methodology for photographing streamers is detailed in Section 3.3.2.

3.2 Test Objects

3.2.1 Properties of the Liquids

There are three types of insulating liquids used in the experiments, including Gemini X (a conventional mineral oil), Diala S4 ZX-I (a synthetic hydrocarbon manufactured
through GTL processes) and MIDEL 7131 (a synthetic ester). Gemini X is an inhibited (anti-oxidative) mineral oil manufactured by NYNAS, which is mainly composed of paraffinic, naphthenic, and a small amount of aromatic compounds. Paraffinic and naphthenic compounds are saturated hydrocarbons, whereas aromatics contain unsaturated benzene rings. The water saturation level of Gemini X is 55 ppm at 20ºC.

Diala S4 ZX-I is an inhibited hydrocarbon liquid produced by Shell using GTL technology. Base oils are first produced from methane (natural gas) through gasification, synthesis and refining processes, which are then used to manufacture transformer oil [146]. Diala S4 ZX-I has a water solubility of about 49 ppm at 20ºC.

MIDEL 7131, which is manufactured by M&I Materials, is a synthetic ester identified by four fatty acid chains and is produced from pentaerythritol. It has a higher flash point and a superior biodegradability compared with Gemini X and Diala S4 ZX-I. At 20ºC, its water saturation level is about 2000 ppm. Some additional information about the three liquids is provided in Table 3-2. Chapters 4 to 6 do not use the trade names of the three liquids. Gemini X, Diala S4 ZX-I and MIDEL 7131 are referred as the mineral oil, GTL oil and synthetic ester, respectively.

### 3.2.2 Preparation of Liquid Samples

Liquid samples used in the experiments are filtered, dehydrated and degassed to minimise the effect of contamination. The pore size of the filters is 0.2 µm. Dehydration process is carried out at 85°C, 500 Pa (500 mBar). Because of the different water saturation levels, Gemini X and Diala S4 ZX-I samples are dried for 48 hours, whereas MIDEL 7131 ones are dried for 72 hours. Treated liquid samples have a relative humidity of less than 10% at 20ºC and are at the ‘low’ contamination level in accordance with the designation in [147]. In this study, all the experiments are carried out at room temperature (20ºC).
Table 3-2. Key properties of the three insulating liquids used in the experiments [148-150]

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Gemini X</th>
<th>Diala S4 ZX-I</th>
<th>MIDEL 7131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 20ºC</td>
<td>kg/dm(^3)</td>
<td>0.870</td>
<td>0.805</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>(ISO 12185)</td>
<td>(ISO 3675)</td>
<td>(ISO 3675)</td>
<td>(ISO 3675)</td>
</tr>
<tr>
<td>Viscosity</td>
<td>mm(^2)/s</td>
<td>9.2 at 40ºC (ISO 3104)</td>
<td>9.6 at 40ºC (ISO 3104)</td>
<td>28 at 40ºC (ASTM D 445)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>820 at -30ºC (ISO 3104)</td>
<td>382 at -30ºC (ISO 3104)</td>
<td>1400 at -20ºC (ASTM D 445)</td>
</tr>
<tr>
<td>Relative permittivity/dielectric constant</td>
<td>-</td>
<td>2.2</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Pour point</td>
<td>ºC</td>
<td>-51 (ISO 3016)</td>
<td>-42 (ISO 3016)</td>
<td>-60 (ISO 3016)</td>
</tr>
<tr>
<td>Flash point</td>
<td>ºC</td>
<td>150 (ISO 2719)</td>
<td>191 (ISO 2719)</td>
<td>260 (ISO 2719)</td>
</tr>
<tr>
<td>Acidity/neutralisation</td>
<td>mg KOH/g</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IEC 62021)</td>
<td>(IEC 62021-1)</td>
<td>(IEC 62021 9.11)</td>
</tr>
<tr>
<td>Water content</td>
<td>mg/kg</td>
<td>&lt; 20 (IEC 60814)</td>
<td>6 (IEC 60814)</td>
<td>50 (IEC 60814)</td>
</tr>
<tr>
<td>Dielectric dissipation factor (DDF) at 90ºC</td>
<td>-</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IEC 60247)</td>
<td>(IEC 60247)</td>
<td>(IEC 60247)</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>kV</td>
<td>40-60 before treatment</td>
<td>60 before treatment</td>
<td>&gt;75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IEC 60156)</td>
<td>(IEC 60156)</td>
<td>(IEC 60156)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;70 after treatment</td>
<td>75 after treatment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(IEC 60296)</td>
<td>(IEC 60156)</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Measurement Methodology

3.3.1 PD Measurement

In order to better examine the dependence of PD characteristics on liquid type, liquid condition and electric field uniformity, measurements are undertaken in a wide voltage range, i.e. from PDIV to near to breakdown level. The breakdown voltages of the three types of insulating liquids are examined in the preliminary tests to ensure that the applied voltage is below the breakdown level during the measurements.

The method recommended by the IEC 61294 for measuring the PDIV of a liquid is to continuously increase voltage at a rate of 1 kV/s [11]. For the purpose of obtaining PD patterns, step increases in the applied voltage are adopted. The measuring duration is set at 1 minute, which is a compromise between the representativeness of the recorded partial discharges and blunting of the needle tip. Therefore, to measure the PDs of the liquid samples, the voltage is increased to the desired level and subsequently maintained to allow a 1 minute recording through the PD detector. After the recording is finished, the voltage is decreased to zero and the liquid sample is left for 1 minute before the next voltage level is applied. The voltage is increased in steps of 1 kV for the determination of PDIV and is increased in steps of 5 kV for the recording of PD pattern at higher voltages.

To obtain one set of PD measurements, the applied voltage is applied from 3 kV lower than the inception level to 55 kV. At each voltage, a 1-minute recording of the PD pattern is obtained. For each set of measurements a new needle electrode is used. Calibration of the measuring system and noise check are performed prior to each set of measurements. One oil sample is only used for two sets of measurements. In total, six sets of PD measurements are carried out using three oil samples. The test cell is emptied, cleaned and dried before it is filled with a different type of liquid sample.

The PD characteristics of liquids are obtained through the post-analysis of the patterns. Based on a PD pattern, as demonstrated in Figure 3-3, the apparent charge of each
discharge and the total number of discharges can be obtained. In this research, the PD magnitude of a liquid at a certain voltage is represented by the maximum apparent charge registered at that voltage and the pulse repetition rate indicates the number of PDs detected during the 1-minute recording. Small discharges that have an apparent charge of less than 10% of the largest detected apparent charge are not counted. As the applied voltage is increased in steps, PDIV defined by a certain apparent charge threshold cannot be determined directly. To calculate the PDIV of a liquid sample, the PD patterns that are obtained using the initial detection range (0 - 650 pC) are analysed. The starting voltage level is 3 kV below the expected inception voltage and the applied voltage is increased in steps of 1 kV. At each voltage the PD pattern is recorded for 1 minute. There is a 1 minute resting time between two measurements to allow the oil sample to settle down. Based on the PD patterns, the PD magnitude (the largest apparent charge) at each voltage can be obtained. By applying linear fitting to the PD magnitude measurements, the best-fit line describing the relationship between PD magnitude and applied voltage can be determined. When the PD magnitude is specified, the best-fit line allows the calculation of the corresponding voltage. In this study, the PDIV is calculated according to the voltage at which the PD magnitude equals 100 pC. This choice of apparent charge threshold complies with the IEC 61294.

![PD pattern example](image)

**Figure 3-3.** An example of the PD pattern of the synthetic ester at 45 kV (NP configuration, gap spacing = 40 mm; 3000 AC voltage cycles)

### 3.3.2 Streamer Measurement

Synchronised streamer photographs and current waveforms are taken in parallel with the
PD measurements. The TTL trigger signal is generated from the trigger unit (Oscilloscope 2, Agilent MSO8104A) once the input signal has an amplitude exceeding the trigger level. When capturing positive streamers, an output from the PD detector is utilised as the input to Oscilloscope 2. The amplitude of this output signal is proportional to the apparent charge of the discharge. When capturing negative streamers, because the charge transfers are too small to be detected by the PD detector, Oscilloscope 2 is set to be triggered directly by the streamer current pulses. The triggering processes are illustrated in Figure 3-4. For both positive and negative streamers, the selection of trigger level gives a triggering frequency of about once per minute. The largest PD at each voltage level has the same occurrence frequency of once per minute according to the PD patterns. In this way, the streamers photographed and the PD magnitudes read from the PD patterns correspond with each other. At each voltage level, 10 streamer photographs are obtained. The light is generated by a 650 W halogen lamp, which is 1 m away from the test cell containing liquid samples. In addition, the time for capturing and photographing a streamer is controlled to be less than 30 s to avoid potential heating of the liquid samples from the light source. During the measurements there is no temperature rise in the samples.

Figure 3-4. Trigger mechanisms for positive and negative streamers

The high speed video operates at a frame rate of 20,000 fps; therefore, the time difference between two consecutive frames is 50 µs. The exposure time is set at 49.6 µs. Centre mode is selected so that frames both before and after the triggering time are recorded. Maximum streamer length is in frame 0 (triggering instant) and the following frames never show a further propagation of the streamer. The high speed video system has a memory that can store over 30,000 frames, covering a 1.5 s period of streamer
development. The pixel resolution of the high speed video is 704*520 (366,080 pixels) at 20,000 frames per second. One millimetre of streamer length occupies about 12 pixels in the photographs (one pixel length corresponds to about 83 µm).

Oscilloscope 1 (LeCroy WaveJet 314A, whose bandwidth and sampling rate are 100 MHz and 1GS/s, respectively) can either pick up the waveform of the PD that triggers the measurement or record a number of PD pulses over a larger time scale. The former is used for computing the propagation duration of a streamer, which is normally less than 25 µs. The latter is used for studying space charge effects when the requirement for the resolution of individual pulses is less strict.

Based on a streamer photograph and the corresponding current waveform, the stopping length, propagation duration and average propagation velocity can be measured or derived. The stopping length of a streamer is determined as the longest possible straight distance from the needle tip to a streamer termination. The propagation duration is manifested in the current waveform. With the stopping length and propagation duration of a streamer, the average propagation velocity is derived as the ratio of stopping length to propagation duration. As an example, a positive streamer appearing in the GTL liquid is shown in Figure 3-5. Its stopping length is measured as 17.4 mm. Based on the corresponding current waveform shown in Figure 3-6, the streamer has a propagation duration of 12 µs. The average propagation velocity can be calculated as 17.4 mm divided by 12 µs, which gives 1.4 mm/µs.

The analysis of streamer area is performed in this study and the aim is to qualitatively compare the extent of streamer branching in the three types of liquids. The streamer area is defined as “the apparent area occupied by all streamer branches in the 2D photograph” [151]. This area is measured by using a self-developed MATLAB program that is capable of converting the original images into binary images, counting the pixels of the branches and converting the number of pixels into an area [152].
Figure 3-5. An example of the positive streamers in Diala S4 ZX-I at 45 kV (NP configuration, gap spacing = 40 mm)

Figure 3-6. Waveform of PD pulse accompanying the positive PD shown in Figure 3-5

3.4 Summary

The test circuit used in the experiments consists of a standard arrangement complying with the IEC 60270 for PD measurement, a resistor for wide-band current measurement, a high speed video system for photographing streamers and a trigger system for device synchronisation. Two electrode systems are employed, needle-to-plane (NP) and plane-needle-plane (PNP). So the liquid samples can be tested in electric fields of various uniformities by adjusting the electrode geometry. Three transformer liquids are to be studied, including a mineral oil (Gemini X), a GTL oil (Diala S4 ZX-I) and a synthetic ester (MIDEL 7131). Their basic physical and chemical properties are provided. The sample treatment procedures are detailed. The last part presents the measurement procedures for PD, PD current pulse and streamer and describes how these measurements are synchronised. Examples of PD patterns, streamer photographs and PD current
waveforms are provided. A number of PD and streamer quantities can be derived in the post-processing of the measurement data.
Chapter 4 PD Characteristics of Transformer Liquids in Divergent and Quasi-Uniform AC Fields

This chapter deals with the PD characteristics of the three liquids in electric fields of various uniformities. PDIV measurements are first obtained from different NP and PNP electrode configurations in order to study their dependence on electrode geometry. These measurements are then used to calculate the PD inception fields (PDIF) of the three liquids. At voltages above the inception level, the PD patterns, PD magnitudes and pulse repetition rates of the three liquids are obtained with the two electrode systems at gap spacings of 10 mm, 25 mm and 40 mm. So, a comparison of the PD measurements obtained under different electric field conditions is made. The measurements obtained at the 40 mm gap spacing are further used for comparing the PD patterns, PD magnitudes and pulse repetition rates of the three liquids.

4.1 Determination of PDIV and PDIF

4.1.1 PDIV and PDIF Obtained from NP Configurations

The PDIVs of the three liquids are first investigated in divergent electric fields under NP electrode configurations. The gap spacing is varied between 5 and 50 mm. With increasing gap spacing, PDIV increases, as shown in Figure 4-1 [153]. This agrees with the literature findings [103, 104, 106]. The slopes produced by linear fittings to the PDIV curves are in the range of 0.167 kV/mm to 0.180 kV/mm with adjusted R-squares lying in the range of 0.979 to 0.988. The PDIVs of the three liquids increase almost linearly
with gap spacing under the tested NP configurations and the increasing rates are very close. At the same gap spacing, the mineral oil and GTL oil have very similar PDIVs, which are slightly higher than the PDIV of the synthetic ester.

![Graph showing PDIVs of three liquids as a function of gap spacing under NP electrode configurations](image)

Figure 4-1. PDIVs of the three liquids as a function of gap spacing under NP electrode configurations [153]

The results shown in Figure 4-1 [153] are obtained from 10 different NP configurations. The axisymmetrical models of these electrode configurations are built in COMSOL Multiphysics for the calculation of tip fields at the corresponding PDIVs using the finite element method (FEM). Figure 4-2 provides an example of the meshed needle electrode whose tip radius is 3 µm. The tip region is fine meshed that any further increase in the number of meshes, i.e. mesh density, cannot lead to any change in result. To check the validity of the FEM models, calculation results of tip field are compared with theoretical and literature values. For a needle-to-plane electrode system with a tip radius of 3 µm and a gap spacing of 40 mm, the theoretical estimate of the tip field based on Mason’s equation [124] is 1837 kV/mm at 30 kV_{peak}. At the same voltage, the COMSOL Multiphysics calculation yields a value of 1684 kV/mm. This is slightly lower than the theoretical estimate, possibly because Mason’s equation assumes the plane electrode used is infinitely large. From [154], a needle-to-plane electrode system with a tip radius of 20 µm and a gap spacing of 10 mm produces a tip field of 423 kV/mm at 30 kV_{rms}. By
developing the same model in the COMSOL Multiphysics, a tip field of 470 kV/mm is obtained. Hence, the models are verified by comparing the FEM calculation results with theoretical and literature values.

![Figure 4-2. Meshing at the needle tip for FEM calculations](image)

The calculations of PDIF are based on peak voltages instead of root mean squares, because the PD with the largest apparent charge at a voltage level is commonly detected at a phase angle of around 90°. According to Figure 4-3 [153], the calculated PDIFs of the three liquids under the NP configurations range between 1200 kV/mm and 1600 kV/mm. The PDIF of each individual liquid tends to be independent of gap spacing. The average calculated PDIFs of the mineral oil, GTL oil and synthetic ester are 1471 kV/mm, 1411 kV/mm and 1274 kV/mm, respectively. The mineral oil and GTL oil have very similar PDIFs and the synthetic ester has the lowest PDIF among the three liquids, which reflects the PDIV relationship seen in Figure 4-1 [153].
Chapter 4 PD Characteristics of Transformer Liquids

Figure 4-3. Calculated PDIFs of the three liquids based on the PDIV measurements obtained from NP electrode configurations [153]

4.1.2 PDIV and PDIF Obtained from PNP Configurations

The PDIVs of the three liquids have also been investigated with the PNP configurations. Measurements are first undertaken at a fixed gap spacing of 25 mm. In Figure 4-4 [153], the PDIVs of the three liquids decrease with increasing needle length. This indicates that the plane electrode holding the needle protrusion can effectively reduce the local electric field at the needle tip when the protrusion is short. With the plane electrode on the HV side moving away from the needle tip, the tip field reduction becomes less. When needle length exceeds 30 mm, the influence of the HV plane electrode is insignificant, indicating a divergent electric field similar to that provided by the NP configuration at the gap spacing of 25 mm [155]. If the needle protrusion is sufficiently long, the NP and PNP electrode systems will generate an identical PDIV measurement for each liquid. Generally, the PDIVs of the mineral oil and GTL oil are very similar and the synthetic ester has a relatively lower PDIV.

Figure 4-5 [153] presents the calculated PDIFs of the three liquids using the results depicted in Figure 4-4 [153] and the models of PNP electrode configurations. For each liquid, the PDIF tends to be fairly constant. A gap still exists between the PDIFs of the
synthetic ester and those of the other two liquids. Based on the PDIV measurements obtained from the PNP configurations at the fixed gap spacing, the average PDIFs of the mineral oil, GTL oil and synthetic ester are 1435 kV/mm, 1431 kV/mm and 1220 kV/mm, respectively.

Figure 4-4. PDIVs of the three liquids as a function of needle length (PNP electrode configurations and NP electrode configuration at a fixed gap spacing of 25 mm) [153]

Figure 4-5. Calculated PDIFs of the three liquids based on the PDIV measurements obtained from PNP electrode configurations at a gap spacing of 25 mm [153]
When the plane-to-plane distance is constant, changing the needle length changes the gap spacing in the meantime. At the fixed plane-to-plane distances of 25 and 50 mm, the PDIVs of the three liquids are also found to decrease with increasing needle length, as shown in Figure 4-6 [153]. The results confirm that the shorter the needle is, the more uniform the electric field will be, thereby requiring higher voltages to initiate PD. The PDIV ranking of the three liquids does not change when different electrode configurations are used. The PDIVs of the mineral oil and GTL oil are very similar, which are higher than the PDIV of the synthetic ester. FEM calculations yield consistent tip field results, which are 1393 kV/mm for the mineral oil, 1418 kV/mm for the GTL oil and 1221 kV/mm for the synthetic ester. These results are shown in Figure 4-7 [153].

![Figure 4-6. PDIVs of the three liquids as a function of needle length (PNP electrode configurations at fixed plane-to-plane distances of 25 and 50 mm) [153]](image-url)
Figure 4-7. Calculated PDIFs of the three liquids based on the PDIV measurements obtained from PNP electrode configurations at plane-to-plane distances of 25 and 50 mm [153]

4.1.3 Effects of Electrode Geometry

Figure 4-1 [153], Figure 4-4 [153] and Figure 4-6 [153] have demonstrated the dependence of PDIV on electrode geometry when the same electrode system is used. A comparison of the PDIV measurements from the NP and PNP electrode systems is shown in Figure 4-8. When the gap spacing is small (when the needle length is large for the PNP electrode system at the fixed plane-to-plane distance), the PDIVs measured with the two electrode systems are very close. When the gap spacing is large (when the needle length is small for the PNP electrode system at the fixed plane-to-plane distance), the two electrode systems produce significantly different PDIV measurements. The separation between the two groups of curves describes the effect of the HV plane electrode. The effect is more significant when the needle tip is closer to the HV plane electrode. Depending on the uniformity of the electric field, the PDIV of the liquid can be measured as 10 kV in divergent fields, or it can be up to 60 kV in quasi-uniform fields.

PDIV increases with gap spacing. This is because a higher voltage is needed to produce a field at the needle tip that is greater than the inception threshold. Revealed by the FEM
calculation results, the seemingly diverse results of PDIV generate very similar calculation results of PDIF. Figure 4-9 provides the PDIFs of the three liquids calculated from the PDIV measurements shown in Figure 4-8. Unlike the PDIVs, the PDIFs of transformer liquids tend to be independent of electrode geometry provided that the tip radius remains constant. So the inception thresholds of the liquids remain unchanged when the gap spacing or needle length varies.

Figure 4-8. A comparison of the PDIV measurements obtained from NP and PNP electrode configurations (for PNP configurations, the plane-to-plane distance is fixed at 50 mm)

Figure 4-10 [153] includes the average PDIFs of the three liquids that are calculated based on the PDIV measurements from the entire 30 NP and PNP electrode configurations. The mineral oil, GTL oil and synthetic ester have a PDIF of 1430 kV/mm, 1419 kV/mm and 1238 kV/mm, respectively. Statistically, the PDIFs of the mineral oil and GTL oil are inseparable. The synthetic ester has the lowest PDIF among the three liquids (about 13% lower compared with the average PDIFs of the mineral oil and GTL oil). The curve of streamer inception field under AC, which is previously shown in Figure 2-14, gives an inception threshold of roughly 2800 kV/mm for the tip radius of 3 µm. Although this literature value and the calculated PDIF of the mineral oil in this
study have different definitions of inception threshold, they are of the same order of magnitude. In both studies, the calculated PDIFs have not taken the space charge effect into consideration. Therefore, the values could be overestimated.

Figure 4-9. Calculated PDIFs based on the PDIV measurements shown in Figure 4-8

Figure 4-10. Average PDIFs of the three liquids based on the PDIV measurements obtained from the 30 electrode configurations [153]
4.2 PD Characteristics at Voltages above PDIV

The PD characteristics of the three liquids are also investigated at voltages above PDIV with the NP and PNP electrode systems, with focus given to the PD pattern, PD magnitude and pulse repetition rate. Various gap spacings are used for both electrode systems and a plane-to-plane distance of 50 mm is chosen for the PNP electrode system. With such selections of electrode geometry, the PD characteristics of the liquids are examined and compared in quasi-uniform electric fields as well as divergent electric fields.

4.2.1 Dependence of the PD pattern, PD Magnitude and Pulse Repetition Rate on Electrode Geometry

Similar to the PDIV, the PD pattern, PD magnitude and pulse repetition rate at higher voltages also appear to be sensitive to the electrode geometry used in the experiments. The PD patterns of the three liquids obtained with the NP and PNP configurations at the gap spacing of 40 mm are provided in Figure 4-11 to Figure 4-13. Under divergent field conditions (produced by the NP electrode configuration), all PDs that occur in the three liquids have phase angles between 40° and 120° at 20 kV and exhibit a ‘mountain-shaped’ distribution. With increasing voltage, the phase angle range increases and at 45 kV the onset of PD can be detected from a phase angle of about 10°. In divergent fields, negative PDs are detected from the synthetic ester.

In Figure 4-11 to Figure 4-13, fewer and smaller PDs occur under the PNP configuration at the gap spacing of 40 mm as compared with the situation when the NP configuration is used. Under quasi-uniform field conditions (produced by the PNP electrode configuration), the PD patterns of the three liquids comprise only positive discharges, resembling those recorded when the HV plane electrode is absent (NP configuration at the gap spacing of 40 mm) but at lower voltages. As the HV plane electrode suppresses the electric field, at most voltage levels in quasi-uniform fields the discharges lie in the phase angle range of 45° to 135°. These discharges still show a ‘mountain-shaped’
distribution as in divergent fields.

![Graphs showing PD patterns in different electric fields](image)

**Figure 4-11.** PD patterns of the mineral oil in divergent and quasi-uniform electric fields at the gap spacing of 40 mm (3000 AC cycles; NP electrode configuration: gap spacing = 40 mm; PNP electrode configuration: gap spacing = 40 mm, needle length = 10 mm)

Under the NP and PNP electrode configurations, PDs are still induced by the needle tip and their propagation ability plays a critical role in causing breakdown. Compared with negative PDs, positive PDs, which have a stronger propagation ability in divergent and quasi-uniform fields, are more easily detected due to the greater charge transfer at the propagation stage.
Figure 4.12. PD patterns of the GTL oil in divergent and quasi-uniform electric fields at the gap spacing of 40 mm (3000 AC cycles; NP electrode configuration: gap spacing = 40 mm; PNP electrode configuration: gap spacing = 40 mm, needle length = 10 mm)

The PD patterns have reflected the dependence of the PD magnitude and pulse repetition rate on electrode geometry at the 40 mm gap spacing. For more detailed analysis of the changes in these two quantities, Figure 4.14 to Figure 4.16 include the PD magnitudes and pulse repetition rates of the three liquids obtained with the NP and PNP configurations at gap spacings of 10 mm, 25 mm and 40 mm. As the plane-to-plane distance is fixed at 50 mm for the PNP configurations, a large gap spacing implies a small needle protrusion length.

At the 10 mm gap spacing, the breakdown voltage for all three liquids is below 20 kV and the measurements are only obtained at 15 kV. The NP and PNP electrode configurations generate similar PD magnitudes and pulse repetition rates for the individual liquids. At the 25 mm gap spacing, the PD magnitudes and pulse repetition
Chapter 4 PD Characteristics of Transformer Liquids

rates obtained from the NP and PNP configurations start to deviate and the measurements obtained from the NP configurations are higher. At the 40 mm gap spacing, the differences in the PD magnitude and pulse repetition rate are further amplified and the measurements obtained from the NP configurations become much higher.

![PD Patterns](image)

**Figure 4-13.** PD patterns of the synthetic ester in divergent and quasi-uniform electric fields at the gap spacing of 40 mm (3000 AC cycles; NP electrode configuration: gap spacing = 40 mm; PNP electrode configuration: gap spacing = 40 mm, needle length = 10 mm)

With a fixed electrode configuration, the PD magnitude and pulse repetition rate increase with applied voltage. Under each electrode configuration, the PD magnitude and pulse repetition rate increase with decreasing gap spacing if the same voltage is applied, because shortening the gap increases the electric field intensity. At the same gap spacing, the presence of the plane electrode can lead to smaller PD magnitude and pulse repetition rate measurements. This effect can be insignificant at the gap spacing of 10 mm, since the two electrode systems provide similar divergent fields. In contrast, the reduction in
the measurements is very obvious with the gap spacing of 40 mm.

Figure 4-14. PD characteristics of the mineral oil obtained with different NP and PNP configurations: (a) PD magnitude and (b) pulse repetition rate (the plane-to-plane distance is set at 50 mm for the PNP configurations)

Figure 4-15. PD characteristics of the GTL oil obtained with different NP and PNP configurations: (a) PD magnitude and (b) pulse repetition rate (the plane-to-plane distance is set at 50 mm for the PNP configurations)
Figure 4-16. PD characteristics of the synthetic ester obtained with different NP and PNP configurations: (a) PD magnitude and (b) pulse repetition rate (the plane-to-plane distance is set at 50 mm for the PNP configurations)

4.2.2 Comparisons of the PD Pattern, PD Magnitude and Pulse Repetition Rate

The NP and PNP electrode systems provide the most different field conditions when the gap spacing is 40 mm, according to Figure 4-14 to Figure 4-16. Therefore, the results obtained at the 40 mm gap are used for comparing the PD patterns, PD magnitudes and pulse repetition rates of the three liquids. Referring to the PD patterns in Figure 4-11 to Figure 4-13, only a small amount of PD activity is detected from the mineral oil. The pulse repetition rate of the GTL oil is higher than that of the mineral oil but is lower than that of the synthetic ester. With increasing stress, more discharges appear and the PD magnitude also increases. But the synthetic ester still exhibits a much higher discharge frequency than the other two liquids, which can be seen from the different densities of the dots representing PDs.

At up to 40 kV in divergent electric fields, only positive discharges are detected in the mineral oil and GTL oil. However, in the synthetic ester, negative discharges occur as well as positive ones. The analysis of negative discharge currents documented in [97] has evidenced that on average the trains of pulses in esters carry more charges than those in
mineral oil. This may explain why negative PDs are only detected in the synthetic ester, and not in the other two liquids. At the same voltage, positive PDs have a higher PD magnitude than negative ones. So, the PDIVs and PD magnitudes of the three liquids are in this study determined by positive PDs. The pulse repetition rates of the mineral oil and GTL oil are also only related to positive PDs. In the case of the synthetic ester, the pulse repetition rate is numerically equal to the sum of the number of PDs under both polarities. Besides the discharge frequency, the appearance of negative PDs is another key difference that can be observed from the PD patterns in divergent fields.

In quasi-uniform fields, all three liquids do not have any detectable discharge activity in negative half voltage cycles. But the different numbers of positive PDs in the three liquids can still be observed from the PD patterns. Generally, in the electric fields provided by the NP and PNP configurations, positive PDs are always more intense than negative ones in terms of apparent charge and frequency.

Based on the PD patterns, the PD magnitudes and pulse repetition rates of the three liquids under the NP and PNP configurations are compared in Figure 4-17 and Figure 4-18. Under the NP configuration, both PD magnitudes and pulse repetition rates increase as the applied voltage increases. At the same voltage, the PD magnitude of the mineral oil is higher than that of the GTL oil but lower than that of the synthetic ester. The PD magnitudes of the three liquids are of the same order of magnitude at the same voltage, whereas the pulse repetition rates of the liquids are significantly different. The synthetic ester has a much larger pulse repetition rate than the other two liquids. At 45 kV, the pulse repetition rate of the synthetic ester is almost 7 times that of the GTL oil and is about 126 times that of the mineral oil (logarithmic scale is used in Figure 4-18). Compared to PD magnitudes, pulse repetition rates are more sensitive to liquid type.

Under the PNP configuration, the PD magnitudes and pulse repetition rates of the three liquids increase with applied voltage in the tested voltage range. The PD magnitudes of the mineral oil and GTL oil become statistically inseparable in quasi-uniform fields, but they are still lower than the PD magnitude of the synthetic ester. The differences in the
pulse repetition rates of the three liquids remain very obvious in quasi-uniform fields and the pulse repetition rates of the liquids follow the same order as in divergent fields.

Figure 4-17. PD magnitudes of the three liquids in divergent and quasi-uniform electric fields (NP electrode configuration: gap spacing = 40 mm; PNP electrode configuration: gap spacing = 40 mm, needle length = 10 mm)

Figure 4-18. Pulse repetition rates of the three liquids in divergent and quasi-uniform electric fields (NP electrode configuration: gap spacing = 40 mm; PNP electrode configuration: gap spacing = 40 mm, needle length = 10 mm)
4.3 Summary

This chapter presents the PD characteristics of the three transformer liquids under various electric field conditions. To alter the electric field condition in the experiments, a plane-to-plane electrode system with an adjustable needle protrusion (plane-needle-plane electrode system) is used as well as a conventional needle-to-plane electrode system. The PD characteristics of the three liquids are compared in terms of PDIV, PDIF, PD pattern, PD magnitude and pulse repetition rate. The results suggest that the PDIVs of the three liquids increase with increasing uniformity of the electric field. The calculated PDIFs of the three liquids are, however, fairly constant for the tip radius used. Hence, the PDIVs of the three liquids depend on electrode geometry, whereas the PDIFs do not. The average PDIFs of the mineral oil, GTL oil and synthetic ester are 1430 kV/mm, 1419 kV/mm and 1238 kV/mm, respectively. The PDIF of the synthetic ester is about 13% lower than the PDIFs of the mineral oil and GTL oil.

Based on the PD measurements obtained at voltages higher than the PDIV, the PD magnitude of the synthetic ester is the highest among the three liquids under both NP and PNP configurations. The PD magnitude of the mineral oil is higher than that of the GTL oil under the NP configuration, but no obvious difference is observed under the PNP configuration. The three liquids exhibit quite different pulse repetition rates, which are observable from the PD patterns. Under both NP and PNP configurations, the synthetic ester has the highest pulse repetition rate among the three liquids and the mineral oil has the lowest. Compared with PD magnitudes, pulse repetition rates are more sensitive to the composition of a liquid.
Chapter 5  Streamer Characteristics of Transformer Liquids in Divergent AC Fields

The characteristics of streamers in transformer liquids have attracted extensive research efforts since the results contribute to the understanding of the mechanisms responsible for the breakdown in liquids [113]. The most typical approach is to stress the liquid sample with divergent electric fields and to photograph the development of streamers in the liquid. In most cases, impulse voltages are used to allow concurrent streamer generation and streamer measurement.

This chapter discusses the streamer characteristics of the three liquids in divergent electric fields under AC stress. The NP electrode system is used with a gap spacing of 40 mm. Liquid samples are filtered and dehydrated prior to the measurements. Streamers that appear in the insulating liquids are photographed using the Shadowgraph technique. The photographs obtained are then used for the qualitative analysis of streamer physics, e.g. streamer shape, stopping length and streamer area. As the time of streamer propagation is available from the current waveform, the average propagation velocity can be calculated. The dependence of these streamer physics on voltage amplitude, voltage polarity and liquid type is discussed.

Both positive and negative streamers can occur under AC. The physics of the positive streamers in the three liquids are investigated in a wide voltage range and their correlations with PD measurements are established. Negative streamers have different features from positive ones. The negative streamers that appear in the mineral oil and GTL oil do not propagate. Therefore, the propagation behaviour of the negative streamers is only analysed for the synthetic ester. The effects of space charge on streamer propagation are observed from the behaviour of consecutive streamers in the synthetic ester at 45 kV.
5.1 Initiation and Propagation of Positive Streamers in Divergent Electric Fields

The characteristics of the positive streamers in the three liquids are examined between 20 kV and 45 kV. A typical waveform of the currents accompanying positive streamers is provided in Figure 5-1. The current signal contains high-frequency oscillations that are superimposed on a lower frequency positive pulse. The amplitude and duration are in the scale of mA and µs, respectively. The time integral of this current gives a charge of approximately 2000 pC, which is compatible with the maximum apparent charge reading at 45 kV from the PD detector. With increasing voltage level, both the amplitude and duration of the signal increase. This indicates that a greater amount of charge transfer will take place as the electrical stress increases, supporting the results discussed in [156].

![Figure 5-1. Typical waveform of positive streamer current in the GTL oil at 45 kV (NP configuration, gap spacing = 40 mm, bandwidth of the D.S.O. = 100 MHz)](image-url)

As shown in Figure 5-2, at 20 kV, which is slightly higher than the PDIVs of the liquids, small positive streamers appear near the needle tip and most of them comprise two branches. Once the applied voltage is increased, more branches appear and positive streamers grow further. The relatively long branches of the positive streamers in the three liquids have a similar diameter, so the number and length of these branches are the main factors that determine the shadow area in a streamer photograph. Smaller side branches
and offshoots originate from large branches. They can also affect the area of shadow regions.

The shapes of streamers reflect how streamer propagation takes place in liquids. Positive streamers are encountered in all three liquids and their propagation needs a strong electric field at the streamer tip for extracting electrons. The streamer tip at the streamer propagation stage has a similar function to the needle tip at the streamer initiation stage. The high field extraction can vaporise and dissociate the liquid [120], thereby increasing the volume of the gaseous streamer channel during propagation. When a streamer branch propagates, it generally follows the directions of the electric field, because electrons are pulled towards the field region in the opposite direction. For this reason, in regions near the needle tip, the electric field is highly divergent and radial streamer branches are always seen. The direction of the high field extraction can change during streamer propagation. This results in tree-shaped streamer structures, where only small straight segments exist. A streamer branch can also split during propagation. This means that its termination acts as the anode tip and initiates new branches. The new branches can propagate or cease growing, depending on the field at their terminations. If they propagate, they may change propagation direction or split. The same processes are repeated during streamer propagation.

At below 40 kV, the longest branch can be in different radial directions. But at voltages equal to or higher than 40 kV, the longest branch more likely occurs in the axial direction (normal to the plane electrode). Two types of branches are observed, i.e. main branches and side branches. Main branches refer to the streamer channels that originate from the needle tip. Side branches originate from main branches. Their propagation starts from the nodes on the main branches where the streamer splits. When side branches split, smaller side branches appear. These new side branches produced often cease propagating after a short distance and are named offshoots in this thesis. Generally, offshoots have a much smaller length than the main and side branches. From Figure 5-2 it is seen that the positive streamers in the synthetic ester have more offshoots on the branches than those in the other two liquids.
Figure 5-2. Sample photographs of positive streamers in divergent fields at 20 kV to 45 kV
Based on the 2D streamer photographs and the corresponding current waveforms, the stopping lengths, areas, propagation durations and average propagation velocities of the streamers are quantified. As previously emphasised, the stopping length is determined as the longest possible distance from the needle tip to a streamer termination. Figure 5-3 includes the average stopping lengths of the positive streamers in the three liquids. It shows that positive streamers increase in length with increasing voltage level. In divergent electric fields, the positive streamers that appear in the three liquids tend to have a very similar ability to propagate, as can be seen from the similar stopping lengths at the tested voltages. The increasing rate of positive streamer stopping length with respect to applied voltage is 0.5 mm/kV to 0.6 mm/kV.

![Figure 5-3. Stopping lengths of positive streamers in divergent fields as a function of applied voltage](image)

The positive streamers in the liquids have a similar stopping length; however, it does not mean that the extent of branching is the same. As the main stems forming the positive streamers are observed to have a similar diameter, the extent of branching can be qualitatively compared based on streamer area. Figure 5-4 provides the calculated areas of positive streamers in the three liquids. The streamer area in this research is defined as “the apparent area occupied by all streamer branches in the 2D photograph” [151]. This
area is measured by using a self-developed MATLAB program that is capable of converting the original images into binary images, counting the pixels of the branches and converting the number of pixels into an area [152]. In Figure 5-4, the positive streamers in the mineral oil and GTL oil have an overall similar degree of branching in the tested voltage range. The positive streamers in the synthetic ester branch more than those in the other two liquids.

Figure 5-4. Areas of positive streamers in divergent fields as a function of applied voltage

The propagation durations of the positive streamers increase with applied voltage, as can be seen from Figure 5-5. Based on the stopping length and propagation duration of a streamer, the average propagation velocity is derived as the ratio of stopping length to propagation duration and is presented in Figure 5-6. Results show that all the positive streamers detected in the three liquids are 2\textsuperscript{nd} mode streamers since their average propagation velocity lies in the range of 1.0 mm/µs to 2.0 mm/µs [157]. In the tested voltage range, the positive streamer propagation velocities of individual liquids are fairly constant. This is the most probable situation under AC stress as the shift of positive streamer propagation mode from 2\textsuperscript{nd} to 3\textsuperscript{rd} or 4\textsuperscript{th} needs overvoltages that exceed the breakdown voltage [157, 158].
Chapter 5 Streamer Characteristics of Transformer Liquids in Divergent AC Fields

Figure 5-5. Propagation durations of positive streamers in divergent fields as a function of applied voltage

Figure 5-6. Average propagation velocities of positive streamers in divergent fields as a function of applied voltage
5.2 Initiation and Propagation of Negative Streamers in Divergent Electric Fields

The negative streamers that appear in the liquids are also investigated and their current waveforms are different from those of positive streamers. In Figure 5-7, the current accompanying a negative streamer consists of pulses with increasing amplitude and separation. The pulses have a very small duration, leading to a charge quantity inseparable from the background noise for the mineral oil and GTL oil. The train of discrete pulses indicate a series of electron injections from the cathode, which triggers electron avalanches for negative streamer propagation.

Figure 5-7. Typical waveform of negative streamer current in the GTL oil at 45 kV (NP configuration, gap spacing = 40 mm, bandwidth of the D.S.O. = 100 MHz)

Comparisons of streamer shape are made in a voltage range of 35 kV to 45 kV. As illustrated in Figure 5-8, negative streamers look like small extensions from the needle tip at the initiation stage, which are hard to be observed. The negative streamers that appear in the mineral oil and GTL oil at 35 kV do not contain any obvious branches, whereas those in the synthetic ester exhibit clear treeing structures with one or two main branches. After the applied voltage is further raised, negative streamers in the mineral oil and GTL oil do not show any obvious change in shape and size. In contrast, those in the synthetic ester elongate and many more branches appear. Similar to the current
waveform, the streamer shape changes significantly with voltage polarity. Negative streamers usually have thicker branches than positive ones. This is in accordance with the results obtained under impulse stress [159].

Figure 5-8. Sample photographs of negative streamers in the three liquids at 35 kV to 45 kV

Figure 5-8 shows that the negative streamers in the mineral oil and GTL oil do not propagate. This may be a result of the insufficient field intensity for negative streamers to elongate in these two oils [4]. The propagation threshold for negative streamers tends to differ with liquid type as the propagation of negative streamers is not hindered in the synthetic ester. Figure 5-9 presents the stopping lengths of the negative streamer in the synthetic ester. A linear increase of the stopping length with applied voltage can be observed and the increasing rate is about 0.7 mm/kV. The different negative streamer propagation behaviours could be related to the differences in electronegativity caused by electron scavengers, which for the synthetic ester may be the electronegative oxygen
The negative streamers in the synthetic ester propagate further as voltage increases. With increasing voltage level, their durations also increase, as shown in Figure 5-10. The variations in the propagation duration are mainly caused by the discrete-pulse feature of negative discharges. The variations have also brought uncertainties to the derived average propagation velocities of negative streamers, as can be seen from Figure 5-11. Depending on the polarity of applied voltage, streamers have different characteristic velocities. Negative streamers have a lower average propagation velocity of less than 0.7 mm/μs compared with positive ones. This agrees with the different characteristic velocities of positive and negative streamers reported in [113, 120, 160].
Chapter 5 Streamer Characteristics of Transformer Liquids in Divergent AC Fields

Figure 5-10. Propagation durations of negative streamers in divergent fields as a function of applied voltage

Figure 5-11. Average propagation velocities of negative streamers in divergent fields as a function of applied voltage

Figure 5-12 includes the stopping length measurements of both positive and negative streamers. At the same voltage, the positive streamers in the synthetic ester have a longer stopping length than the negative ones. This is also true for the mineral oil and GTL oil
where the negative streamers do not propagate. The positive streamers in the three liquids have a stronger ability to propagate than negative ones. So positive streamers are the dominant causes of breakdown in the divergent AC fields, which is compatible with the experimental results reported in [4]. Under impulse stress, negative streamers also have a weaker propagation ability than positive ones, which has been discussed in [161].

Figure 5-12. Stopping lengths of positive and negative streamers in divergent fields as a function of applied voltage

### 5.3 Correlations between PD and Streamer Characteristics

A streamer is dangerous if it propagates far, because it can normally cause an electrical breakdown of the insulating liquid once a complete bridge is formed between the electrodes. Stopping length is perhaps one of the most important physical features of a streamer, as it is a direct indicator of how close the pre-breakdown disturbance is to triggering breakdown. In practical scenarios, insulation performance is often assessed based on PD measurements. Apparent charge has been the most common one since it is used as the key indicator of insulation integrity in standard short- and long-duration AC withstand voltage tests for high voltage equipment, e.g. power transformers. The
dependence of streamer stopping length and apparent charge on electrical stress is very clear. Under higher stress, streamers will propagate further, showing a longer stopping length, and the PD magnitude will also rise. Synchronised measurements of the streamer stopping length and PD magnitude are rarely undertaken for transformer insulating liquids. In this research, photographing streamers in transformer liquids in parallel with PD measurements allows the correlations between streamer stopping length and apparent charge to be established for transformer insulating liquids.

Negative PDs are only detected from the synthetic ester at high voltages. Figure 5-13 provides the PD magnitudes of the three liquids with the data of positive and negative PDs separately given for the synthetic ester. Like positive discharges, negative discharges in the synthetic ester increase in magnitude with applied voltage. The apparent charge measurements shown in Figure 5-13 indicate that the three liquids experience different levels of positive PD at the same voltage. Comparing the insulation performance of transformer liquids based on apparent charge may give an impression that the PDs in the synthetic ester are more dangerous. This could be misleading. The streamers in the three liquids are in fact equally dangerous since they have an almost identical stopping length at the same voltage, as revealed in Figure 5-3.

![Figure 5-13. PD magnitudes of the three liquids as a function of applied voltage (magnitudes of positive and negative PD are separated for the synthetic ester)](image)
Chapter 5 Streamer Characteristics of Transformer Liquids in Divergent AC Fields

Figure 5-14 presents the streamer stopping length as a function of maximum apparent charge in order to better understand the relationship between the two measurements. At an apparent charge level of less than 1200 pC, the stopping length of the positive streamers is less than 7 mm, which is not distinct enough for recognizing any difference in the increasing rates of stopping length with apparent charge. At an apparent charge level equal to or greater than 1200 pC, the liquids exhibit rather different efficiencies in turning the charge input into streamer stopping length, with the GTL oil being the highest and the synthetic ester being the lowest. When a fixed apparent charge threshold is adopted, for example at 2000 pC, the GTL oil will actually suffer from more dangerous positive streamers than the other two liquids. When streamers with the same stopping length appear in the three liquids, 15 mm for example, the PD magnitude of the GTL oil can be 500 pC lower than that of the mineral oil and 900 pC lower than that of the synthetic ester. So, liquid chemistry affects the correlation between streamer stopping length and apparent charge. When comparing the insulation performances between insulators or insulation systems, conclusions, based solely on apparent charge values, can be misleading.
Negative streamers in the synthetic ester have a smaller stopping length and PD magnitude than positive ones at the same voltage. In Figure 5-14, these negative streamers have a greater stopping length per unit of apparent charge compared with positive ones.

The different charge amounts needed for the formation of positive streamers of equal length in the three liquids can be a result of different degrees of branching. As for a positive streamer, when its branches elongate, electrons are attracted towards the streamer and penetrate into the gaseous phase. This process, which has been recognised as the charge amplification process [120, 162], leads to an increased net positive charge on the streamer head. So during propagation, the branches forming a positive streamer can gain more charges, as illustrated in Figure 5-15 [120]. If sufficient positive charge has been gained at a certain point, branching can happen together with charge splitting [120, 162]. At that point, the total charge level is unchanged. The reason is that charge splitting should obey the charge conservation law. Therefore, as can be seen from Figure 5-15 [120], the sum of the charges carried by each new branch is equal to the charge amount at the termination before charge splitting happens. Thereafter, the same charge amplification and charge splitting processes can happen to the new branches. When the streamer ceases growing, the total charge is the sum of charges at all the terminations [120]. Hence the branching tendency of a streamer can influence the total charge or energy transfer at the propagation stage.

To highlight the differences in the streamer branching behaviour among the three liquids, the calculated areas of positive streamers are plotted with respect to stopping length. When streamers have the same stopping length, those having more side branches and small offshoots are expected to occupy a larger area in the shadowgraph. Hence, the area of a streamer can be used to indicate its branching tendency. In Figure 5-16, positive streamers of the same length have the highest branching tendency in the synthetic ester and the lowest in the GTL oil. In other words, a positive streamer appearing in the synthetic ester is likely to have more side branches than a streamer with an identical stopping length but appears in the mineral oil or GTL oil. Even though these side
branches, especially offshoots, can contribute to a higher apparent charge reading, they do not necessarily alter the severity of the entire streamer, which is determined by the main branch that propagates furthest away from the origin (nearest to the grounded plane electrode).

Figure 5-15. Diagrammatic snapshot of a positive discharge tree [120]

Figure 5-16. Areas of positive streamers as a function of stopping length
5.4 Space Charge Effect

Under AC, occurrences of streamers can be very close in time. An early streamer can leave residual charges in the liquid. Before subsequent streamers occur, some of the residual charges may not have been dissipated. This group of residual charges is considered as space charge. Space charge alters the electric field distribution and affects the initiation and propagation of subsequent streamers, known as the space charge effect.

In this study, the space charge effect is investigated at 45 kV with the synthetic ester whose pulse repetition rate is the highest among the three liquids. 16 streamers are detected within 50 ms (equivalent to 2.5 AC voltage cycles), which are shown in Figure 5-17. The streamers are labelled 1-16 according to their sequence. Positive streamers include Streamers 1, 2, 3, 12, 13 and 16, which can be judged from the polarity of the applied voltage at each time instant. The others are negative streamers.

Space charge can be either homo or hetero, depending on its polarity relative to that of the streamer or needle tip. Homo space charge is present when the needle tip has the same polarity as the preceding streamer, such as in the cases of Streamers 2, 3, 10, 11, 13 and 15. A lowering of the tip field will occur if homo space charge is in the vicinity of the needle tip, which hinders streamer initiation. If a streamer can still be initiated, it tends to bypass the homo space charge at its propagation stage. As can be seen from Figure 5-18, Streamer 1 has its longest branch in the horizontal direction and deposits positive space charge. Consequently, the space charge confines the propagation of Streamer 2 to the vertical direction.

Streamers 10 and 11 are negative, and they are also influenced by the homo space charge left by Streamer 9. After Streamer 9 detaches from the needle tip, the gaseous channel that carries electrons remains present in the synthetic ester. At the beginning, the space charge is close to the needle tip. It is then repelled by the tip field and shrinks with time. Until Streamers 10 and 11 occur, the regions of the negative space charge can still be differentiated from the liquid, which are circled in the two frames in Figure 5-18.
Streamer 10 is very small in size and is indicated by the arrow. Its channel bends significantly due to the homo space charge. In a similar manner, Streamer 11 bypasses the region with homo space charge.

Figure 5-17. 16 sequential current pulses that occur in the synthetic ester at 45 kV in a duration of 50 ms

Hetero space charge means that its sign is opposite to that of the needle tip. This happens when the polarity of the applied voltage reverses, which corresponds to Streamers 4, 12, 14 and 16. Unlike homo space charge, hetero space charge can enhance the local field near the needle tip. Figure 5-17 indicates that Streamer 4 appears when the applied voltage is slightly lower than the zero crossing. This would be highly unlikely without the hetero charge from Streamer 3 easing streamer initiation. As hetero space charge is attracted towards the high field region after polarity reversal; part of it may be neutralised near or on contact with the needle tip. The remaining part alters the field distribution.

When a streamer appears in the presence of hetero space charge, it tends to link the needle tip with the hetero charge. This is seen in streamer photographs as a streamer following the trace of the previous one. For instance, Streamer 14 has a structure similar to the lower part of Streamer 13, and Streamer 16 has a very similar propagation path to Streamer 15.
Chapter 5 Streamer Characteristics of Transformer Liquids in Divergent AC Fields

The photographs displayed in Figure 5-18 prove the existence of the space charge effect in liquid-only environment. However, the quantity and distribution of space charge in the liquid is still hard to specify at the current stage. The space charge effect is essentially a result of the electric field induced by space charge distorting the Laplacian field provided by the needle tip.

![Streamer photographs](image)

Figure 5-18. Streamer photographs corresponding to the 16 sequential current pulses with voltage polarities indicated at the needle tips

### 5.5 Summary

This chapter discusses the streamer characteristics of the three liquids obtained under
divergent electric field conditions. The three key topics are: a) the dependence of stopping length, streamer area and average propagation velocity on voltage amplitude, voltage polarity and liquid type; b) the correlations between the stopping length of positive streamers and apparent charge reading and c) the space charge effect in the synthetic ester.

The positive streamers in the three liquids have a very close stopping length at the same voltage, representing a similar propagation ability across the liquids. These streamers are identified as in 2nd mode of propagation with a fairly constant velocity for individual liquids lying in the range of 1.0 mm/µs to 2.0 mm/µs. Unlike the case under positive polarity, the propagation ability of negative streamers varies with liquid type. In the mineral oil and GTL oil, negative streamers appear without propagating, whereas the streamers in the synthetic ester exhibit a clear treeing structure and the stopping length increases with applied voltage. Overall, negative streamers cannot propagate as far as positive ones at the same voltage level and are therefore unlikely to be the cause of electrical breakdown in the investigated divergent AC fields.

PD measurements performed in parallel with the photographing of streamers demonstrate that the three liquids suffer from positive PDs of different apparent charge levels at the same voltage. This encourages investigation into the correlations between positive streamer stopping length and apparent charge. Among the three liquids, the synthetic ester has the smallest streamer stopping length per unit of apparent charge. This can be related to the different branching tendencies of the positive streamers in the three liquids. The analysis of streamer areas suggests that the positive streamers in the synthetic ester have a higher branching tendency than those in the other two liquids. Likewise, the GTL oil has the lowest branching tendency and has the largest stopping length per unit of apparent charge among the three liquids. Besides liquid type, streamer branching tendency is also dependent on the uniformity of the electric field, which will be discussed in Chapter 6.

In addition, the photographs of 16 consecutive streamers in the synthetic ester prove the
existence of the space charge effect under AC. As a result of the field distortion, a streamer is prone to bypassing the regions containing homo charge and to propagating through the regions containing hetero charge.
Chapter 6 Streamer Characteristics of Transformer Liquids in Quasi-Uniform AC Fields

In addition to liquid chemistry, electric field uniformity can also affect streamer characteristics. The experimental results discussed in Chapter 5 are obtained under divergent field conditions that can ease the formation of streamers and impede electrical breakdown. But the insulating liquids used in power transformers are unlikely to be under such electric field conditions. Therefore, Chapter 6 intends to present the experimental results obtained under quasi-uniform conditions. The PNP electrode system is used in experiments to generate quasi-uniform fields. The plane-to-plane distance is set at 50 mm and the gap spacing is set at 40 mm. Since no negative streamer is captured in quasi-uniform fields, this chapter focuses on the physics of positive streamers. Chapter 6 covers a range of streamer characteristics, including shape, stopping length, area, propagation duration and average propagation velocity. Changes in these streamer characteristics in response to increased electric field uniformity are discussed. By comparing the curves of streamer stopping length against voltage that represent different field conditions, the different propagation abilities of positive streamers are highlighted. Further analysis of this reveals the different dominant factors responsible for electrical breakdown. By establishing the correlations between streamer stopping length and apparent charge and comparing the results obtained under divergent and quasi-uniform field conditions, the field uniformity dependence of the correlation becomes apparent.
6.1 Initiation and Propagation of Positive Streamers in Quasi-Uniform Electric Fields

When the PNP electrode configuration with a 10 mm needle protrusion is used, the electric fields that the liquid samples are subjected to become moderately divergent or quasi-uniform. The plane electrode behind the needle tip effectively alters the electric field distribution and in particular, it lowers the tip field intensity. As a consequence of compensating for the tip field reduction, a profound increase in inception voltage of positive streamers is observed and the margin from PDIV to breakdown voltage is reduced. With regard to the synthetic ester, its streamer and PD characteristics are investigated at 35 kV to 45 kV in quasi-uniform fields. For the mineral oil and GTL oil, the voltage range is 40 kV to 50 kV.

Figure 6-1 provides sample photographs of positive streamers in quasi-uniform fields at both the initiation and propagation stages. At the initiation voltage level, the streamers in the three liquids in quasi-uniform fields comprise one or two small main branches. At the propagation stage, side branches can still occur, but they only occur at a minimum distance of 2 mm from the needle tip. In most cases, there are no more than two main branches originating from the needle tip in quasi-uniform fields with one of them having a much longer stopping length than the other(s). A few side branches appear on the longest main branch.

In Figure 6-2, streamer stopping length increases with applied voltage in quasi-uniform fields at a rate of about 1.1 mm/kV to 1.2 mm/kV. In quasi-uniform fields, the streamers that appear in the mineral oil and GTL oil have a similar stopping length at the same voltage. However, those in the synthetic ester propagate further at the same voltage. So when the electric field becomes more uniform, the positive streamers in the synthetic ester exhibit a stronger propagation ability than those in the other two liquids. This is in accordance with the AC breakdown voltage measurements documented in [95].
With increasing voltage, the streamer area increases due to streamer elongation. According to Figure 6-3, the positive streamers in the synthetic ester have the largest area compared with those in the other two liquids at the same voltage. This can be partially due to the larger stopping length of the positive streamers in the synthetic ester, as illustrated in Figure 6-2. The positive streamers in the mineral oil and GTL oil have a similar stopping length but different areas at the same voltage. Therefore, positive streamers branch more in the GTL oil than in the mineral oil at the same voltage. This conforms to the streamer photographs in Figure 6-1 where the positive streamers in the GTL oil comprise more side branches and offshoots than those in the mineral oil.
Figure 6-2. Stopping lengths of positive streamers in quasi-uniform electric fields as a function of applied voltage

Figure 6-3. Stopping areas of positive streamers in quasi-uniform electric fields as a function of applied voltage

In Figure 6-4, the propagation durations of positive streamers increase with applied voltage in quasi-uniform fields. At the same voltage, the positive streamers in the synthetic ester have a longer propagation duration than those in the other two liquids. As illustrated by Figure 6-5, the derived average propagation velocities of the streamers in
the three liquids lie in the range of 1.2 mm/µs to 2.1 mm/µs. This indicates that the positive streamers observed in quasi-uniform AC fields are still in 2\textsuperscript{nd} propagation mode.

Figure 6-4. Propagation durations of positive streamers in quasi-uniform electric fields as a function of applied voltage

Figure 6-5. Average propagation velocities of positive streamers in quasi-uniform electric fields as a function of applied voltage
6.2 Dependence of Streamer Characteristics on Electric Field Uniformity

According to Figure 6-6, streamer stopping length increases with applied voltage in both divergent and quasi-uniform electric fields. However, the rate of increase is higher in quasi-uniform fields than in divergent fields. For instance, the stopping length of positive streamers in the mineral oil increases linearly at a rate of 1.2 mm/kV in quasi-uniform fields. This value doubles the rate in divergent fields. In divergent fields, the positive streamers in the three liquids have an almost identical stopping length at the same voltage. But this is no longer true under quasi-uniform conditions where the positive streamers in the synthetic ester have a stronger propagation ability than those in the other two liquids.

Figure 6-6. Stopping lengths of positive streamers in divergent and quasi-uniform electric fields as a function of applied voltage

The change of electric field uniformity from divergent to quasi-uniform results in different streamer shapes. At the initiation stage, the shapes of the streamers captured in
divergent and quasi-uniform fields have no clear difference. By increasing the voltage to allow streamers to propagate, differences in streamer shape start to appear. As an example, a comparison of the different shapes of the positive streamers in the mineral oil is made in Figure 6-7 [151]. The positive streamers in the mineral oil have much fewer side branches in quasi-uniform fields than in divergent fields, especially in the region near the needle tip. Although branch splitting can still be observed with the elongation of streamer channel under higher stress, the number of main and side branches does not increase as profoundly as in divergent fields when the applied voltage is increased. So, streamer branching in quasi-uniform fields is significantly suppressed compared with that in divergent fields.

Figure 6-7. Shape change of the positive streamers in the mineral oil as electric field uniformity varies [151]

Under divergent field conditions, the field produced by the sharp needle tip has a radial distribution that favours streamer branching. As a result, at above 25 kV in divergent
fields, multiple main branches are always seen and all of them can promote many side branches and offshoots when they propagate. When the needle tip is in proximity to a plane electrode having the same electric potential, the electric field becomes quasi-uniform and a single dominating branch is usually observed. The reduced number of branches that originate from the needle tip is the key factor that changes the streamer shape. The longest branch is always found in the axial direction (normal to the plane electrode) in quasi-uniform fields. This is in contrast to the case of divergent fields where the longest branch can be in any radial direction at below 40 kV. The visual differences in streamer shape are further analysed by calculating the areas of the streamers, as shown in Figure 6-8. Positive streamers in quasi-uniform fields have much smaller areas than those in divergent fields.

![Figure 6-8. Areas of positive streamers in divergent and quasi-uniform electric fields as a function of applied voltage](image)

If a streamer branch splits during its propagation, its tip charge will split at the same time. Each new branch thus carries a portion of the original charge [162], thereby having a weaker ability to propagate than it did before branching. On the contrary, if a streamer branch propagates without branching, it could gain more charge through charge amplification along its propagation path. For this reason, the change of dominant
breakdown factor, or the different propagation abilities of positive streamers under different field conditions, can be related to streamer branching. To better compare the branching tendencies of streamers that propagate the same distance under the two field conditions, the areas of positive streamers in the three liquids have been analysed as a function of stopping length and the results are shown in Figure 6-9. It is confirmed that streamers of the same length have much smaller areas in quasi-uniform fields than in divergent fields.

According to Figure 6-10, the propagation durations of positive streamers increase with applied voltage in divergent and quasi-uniform fields. In both cases they show a similar trend to the stopping length measurements. Figure 6-11 includes the average propagation velocities of positive streamers in divergent and quasi-uniform fields. It is found that the change of streamer shape under different electric field conditions does not accompany change of streamer propagation mode. In this study, all the positive streamers that appear under AC stress fields are 2nd mode streamers.
Figure 6-10. Propagation durations of positive streamers in divergent and quasi-uniform electric fields as a function of applied voltage

Figure 6-11. Average propagation velocities of positive streamers in divergent and quasi-uniform electric fields as a function of applied voltage
6.3 Change of the Dominant Breakdown Factor in Electric Fields of Different Uniformities

Breakdown in liquids can be ascribed to the appearance of a streamer being able to traverse the whole gap. The roles of the two stages of streamer development, i.e. streamer initiation and propagation, are not equally significant in divergent and uniform electric fields. The different increasing rates of stopping length with respect to applied voltage identified under different electric field conditions in fact imply a change of the dominant cause of breakdown.

In order to combine the results obtained from the two electrode systems, normalised applied voltage is used, which is defined as “the ratio of applied voltage to the corresponding PDIV” [151]. By plotting the stopping lengths of the positive streamers in the three liquids against normalised applied voltage, as the example demonstrates in Figure 6-12, the curves have the same origin and the normalised applied voltage can be understood as an indication of the applied electrical stress relative to the inception level.

![Diagram](image)

Figure 6-12. Stopping lengths of the positive streamers in the mineral oil as a function of (a) applied voltage and (b) normalised applied voltage
Figure 6-13 presents the stopping lengths of the positive streamers in all three liquids with respect to normalised applied voltage. The slope of the curves represents the ability of a streamer to propagate under certain field conditions. When the slope is large, a small increase in the stress can lead to a significant extension of the streamer. In divergent electric fields, streamers can be relatively easily initiated in the three liquids as the inception voltages are lower than 20 kV. But only those propagating far can incur breakdown. This needs a voltage of more than 2.5 times of the PDIV to be applied in the experiments. So, breakdown in divergent fields is primarily governed by streamer propagation. Under quasi-uniform electric field conditions, streamer propagation is to a certain degree facilitated, as indicated by the larger slope of streamer stopping length against normalised applied voltage. From divergent electric fields to quasi-uniform electric fields, streamer initiation becomes more and more dominant over streamer propagation in triggering breakdown [151]. In uniform electric fields, the slope would be extremely large. This indicates that all the streamers can bridge the electrodes once initiated, and therefore, streamer initiation controls breakdown in ideal uniform fields. The results presented in Figure 6-13 prove the existence of such a transition where the dominant breakdown factor can switch under AC stress and support the arguments stated in [4, 163].

Figure 6-13. Stopping lengths of streamers as a function of normalised applied voltage
Positive streamers exhibit different branching tendencies in divergent and quasi-uniform electric fields as reflected by the different streamer areas and streamer shapes. The reason is that the two electrode configurations provide different electric field distributions. Compared with streamer initiation that is mainly governed by the tip field intensity, streamer propagation can also be affected by the directions of electric field lines, as the field direction at a certain point controls the motion of positive ions and electrons.

In order to verify different field distributions between divergent and quasi-uniform fields, static field simulations are performed with COMSOL Multiphysics. Modelling streamer propagation is very challenging because of the interactions between charged particles and the electric fields they are subjected to (which are different from the Laplacian field produced by the needle tip). At the current stage of this research, the electric field distributions are examined without considering the existence of any streamers or space charge. This means that the field simulations are performed for the streamer initiation stage. The results are depicted in Figure 6-14 [151]. The two groups of electric field lines in the figure represent the divergent field and quasi-uniform field conditions separately. The comparison is made within a 5 mm * 5 mm area adjacent to the needle tip. Since the electric field distributions are axisymmetrical; only those in the upper half are demonstrated. The PDIVs (peak values) of the mineral oil are used in the simulations. The arrow length at each point is logarithmically proportional to the field intensity. Therefore, the field intensity at the needle tip is in fact much larger than those at other points.
Chapter 6 Streamer Characteristics of Transformer Liquids in Quasi-Uniform AC Fields

Figure 6-14. Distributions of the static electric fields provided by the NP and PNP electrode configurations (method: FEM calculation with COMSOL Multiphysics; blue arrows: divergent field distribution provided by the NP configuration; green arrows: quasi-uniform field distribution provided by the PNP configuration; arrow lengths are logarithmically proportional to the field intensity) [151]

According to Figure 6-14 [151], the blue arrows are more towards the radial direction than the green ones. This indicates that the electric field lines representing divergent field conditions have larger radial components than those representing quasi-uniform field conditions, except for the lines on the symmetrical axis. In the circled regions, for example, the different radial components of the electric field lines mean that the streamers have a lower probability to propagate towards the radial direction under the PNP configuration than under the NP configuration.
Hence, by using the two electrode systems, electric fields of different uniformities are obtained. The electric field produced by the NP electrode system are generally more towards the radial direction than that produced by the PNP electrode system. This can result in different branching tendencies of the initiation-stage streamers under the two electrode configurations. At the same stopping length, positive streamers branch more in divergent fields than in quasi-uniform fields. Because of the charge splitting that accompanies streamer branching, positive streamers have a stronger propagation ability in quasi-uniform fields. In uniform fields, the streamers would have even stronger propagation ability. In such a case, streamer initiation dominates and breakdown voltage would be the same as PD or streamer inception voltage. Positive streamers can be initiated at a relatively low voltage in divergent fields but a much higher voltage is needed for them to cross half of the gap, meaning that streamer propagation dominates.

6.4 Change of the Correlations between PD and Streamer Characteristics

In divergent electric fields, the three liquids suffer from positive streamers of almost identical length at the same voltage, while different PD magnitudes are registered. In quasi-uniform electric fields, the relationships of the PD magnitudes in Figure 4-17 are similar to those of the streamer stopping lengths in Figure 6-2. This implies that in addition to liquid type, electric field uniformity can also affect the correlation between stopping length and apparent charge. A synthesis of the correlations obtained in divergent and quasi-uniform electric fields is thus provided in Figure 6-15.

As shown in Figure 6-15, in quasi-uniform fields where streamer branching is suppressed, positive streamers have a larger stopping length per unit of apparent charge than in divergent fields. This means that a small increase in apparent charge could indicate a substantial elongation of the streamer main branch. So, when judging the
severity of a defect present in an insulation system, its location that determines the electric field condition shall be treated as an important aspect for consideration. For example, a PD whose magnitude is 500 pC indicates a benign 3 mm long streamer in the mineral oil in the divergent electric field or a much more dangerous 15 mm long streamer in the quasi-uniform electric field. Likewise, a 750 pC PD detected from the synthetic ester indicates a 3 mm long streamer in the divergent electric field. But the same PD level indicates a much longer 13 mm streamer in the quasi-uniform electric field. When streamers of a 10 mm stopping length appear in the three liquids, the apparent charge reading lies in the range of 1500 pC to 2800 pC under quasi-uniform field conditions and lies in the range of 350 pC to 700 pC under divergent field conditions.

![Graph](image)

Figure 6-15. Correlations between streamer stopping length and maximum apparent charge in divergent and quasi-uniform fields

In quasi-uniform fields, the correlations between streamer stopping length and apparent charge are generally close across the three liquids. The calculated areas of the positive streamers in the three liquids are very close at the same stopping length. Therefore, when the uniformity of the electric field is high, the constraint of the branching tendency of streamers can mask the effect of liquid chemistry.
Overall, two major factors have been identified in this research that can influence the evaluation of discharge activity in insulating liquids, which are liquid chemistry and electric field uniformity. This suggests that the use of a fixed apparent charge threshold could be insufficient in real testing where liquid type and PD location can vary. Determining the danger level of PD in practical tests, such as in AC withstand voltage tests, can be much more complicated taking into account the complex insulation structure and irregular source of deficiency. In such cases, the knowledge of PD location will be extremely valuable to the interpretation of PD results.

6.5 Summary

This chapter discusses the characteristics of streamers in quasi-uniform fields. In quasi-uniform fields, only positive streamers are detected from the three liquids. According to the streamer shadowgraphs, the longest main branch always appears in the axial direction. Streamer stopping length increases with applied voltage. At the same voltage, the positive streamers appearing in the synthetic ester have a longer stopping length than those in other two liquids. The average propagation velocities of the positive streamers in the three liquids lie in the range of 1.2 mm/µs to 2.1 mm/µs.

In both divergent and quasi-uniform fields, the detected positive streamers propagate in the 2\(^{nd}\) mode. Despite having the same characteristic velocity, the positive streamers in quasi-uniform fields exhibit a stronger propagation ability than those in divergent fields. By plotting stopping length measurements against normalised applied voltage, it is further disclosed that different breakdown factors exist in electric fields of different uniformities. More specifically, streamer propagation dominates breakdown in divergent electric fields. When the electric field becomes more uniform, streamer initiation is more dominant. The existence of such a transition provides sound evidence for the shift of the dominant breakdown factor under AC stress when the electric field condition changes.

In divergent electric fields, positive streamers that appear in the three liquids have an
almost identical stopping length at the same voltage, whereas differing PD magnitudes of the three liquids are registered. The situation changes in quasi-uniform electric fields, where the PD magnitude relationship of the three liquids becomes valid in reflecting the stopping length relationship. By comparing the different streamer shapes and analysing streamer areas as a function of streamer stopping length, it is found that the branching tendency of positive streamers varies with electric field uniformity as well as liquid type. In divergent electric fields, streamers having a strong branching tendency exhibit a small stopping length per unit of apparent charge, possibly because an increase in the number of branches enables more charge amplification processes to take place. In quasi-uniform fields where streamer branching is largely suppressed for all three liquids, the uniformity of the electric field plays a more significant role than liquid chemistry. For an individual liquid, streamers of the same apparent charge reading will be more dangerous if the electric field to which they are subjected is more uniform. This emphasises the complexity of evaluating the severity of a PD or streamer and the importance of locating the insulation defect.
Chapter 7  Conclusions and Further Work

7.1  Summary of Research Work

In this PhD research, both the PD and streamer characteristics of a mineral oil Gemini X, a GTL oil Diala S4 ZX-I and a synthetic ester MIDEL 7131 were compared and discussed. A plane-needle-plane (PNP) electrode system was used in addition to a needle-to-plane (NP) electrode system, as the aim was to carry out measurements in not only divergent but also quasi-uniform AC electric fields. A standard circuit arrangement that is in compliance with the IEC 60270 was employed for PD measurements. A commercial PD detector, Lemke LDS-6, was used. The streamers that appeared in the three liquids were photographed using the Shadowgraph technique with the aid of a high speed video system. Undertaking PD and streamer measurements simultaneously allowed streamer characteristics, e.g. stopping length measured from a shadowgraph, to be correlated with PD characteristics, e.g. PD magnitude recorded by the PD detector.

This work covers the following research topics:

- PD characteristics of transformer liquids under AC stress:
  - Dependence of the PDIV and PDIF on electrode geometry;
  - Dependence of the PD pattern, PD magnitude and pulse repetition rate on applied voltage and electrode geometry;
  - Comparisons of the PD characteristics among the three liquids;
- Streamer characteristics of transformer liquids under AC stress:
  - Dependence of the streamer shape, streamer area, stopping length and average propagation velocity on voltage amplitude and polarity;
  - Comparisons of the streamer characteristics among the three liquids;
  - Dependence of the streamer characteristics on electric field uniformity;
  - Space charge effect.
• Correlations between PD and streamer characteristics under AC stress and their dependence on liquid type and electric field uniformity.

7.2 Conclusions

PD characteristics of transformer liquids:

The PD characteristics of the three liquids were investigated from PD inception voltage to close to breakdown voltage. At the PD inception level, 30 different electrode configurations were used. As a result, a great dependence of the PDIV on electrode geometry was observed. By calculating the local electric fields at the needle tip using the finite element method (FEM), the PD inception fields of the three liquids were found to be independent of electrode geometry for the investigated tip radius. The average PDIFs of the mineral oil, GTL oil and synthetic ester are 1430 kV/mm, 1419 kV/mm and 1238 kV/mm, respectively. The PDIFs of the mineral oil and GTL oil are thus statistically inseparable and the PDIF of the synthetic ester is about 13% lower than the PDIFs of the mineral oil and GTL oil.

At voltages higher than the inception level, the dependence of the PD pattern, PD magnitude and pulse repetition rate on electrode geometry and liquid type was investigated. When the same gap spacing is used, the PD magnitude and pulse repetition rate obtained from the NP configuration are higher than those obtained from the PNP configuration at the same voltage. When the electrode geometry is fixed, the PDs appearing in the three liquids have PD magnitudes of the same order at the same voltage. However, the pulse repetition rates of the three liquids are significantly different. Among the three liquids, the synthetic ester has the largest pulse repetition rate and the mineral oil has the smallest. Negative PDs were only observed from the synthetic ester in the experiments. Compared with the PD magnitude, the pulse repetition rate is more sensitive to liquid type and liquid condition.
**Chapter 7 Conclusions and Further Work**

*Streamer characteristics of transformer liquids in divergent AC fields:*

The polarity of the needle electrode alternates under AC stress. When the needle electrode acts as an anode, positive streamers can emanate from it. When the needle electrode acts as a cathode, negative streamers can emanate from it. The physics of the streamers in the three insulating liquids, including stopping length, streamer shape, streamer area, propagation duration and average propagation velocity, were investigated in divergent and quasi-uniform electric fields.

In divergent fields, the positive streamers captured have a velocity of 1.0 mm/µs to 2.0 mm/µs, which indicates a 2\textsuperscript{nd} mode of streamer propagation. With increased applied voltage, the main branches of the positive streamers elongate and the streamer branching tendency increases. These are confirmed by the analysis of stopping length and streamer area. Under negative polarity, the streamers initiated in the mineral oil and GTL oil do not propagate. The negative streamers in the synthetic ester, however, propagate further when the applied voltage is increased. The negative streamers that appeared in the three liquids are always smaller and slower than the positive ones at the same voltage; therefore 2\textsuperscript{nd} mode positive streamers are recognised as the primary causes of breakdown in divergent AC fields.

The three liquids suffer from streamers of an identical stopping length at the same voltage, but they at the same time yield different PD magnitude readings. This implies that referring only to apparent charge measurements can be insufficient for the comparison of insulating performance across different types of liquids. Hence the correlations between streamer stopping length, which reveals the severity of a discharge, and apparent charge, which is widely used in the industry as an indicator of insulation defect, were established. Among the three liquids, the stopping length per unit of apparent charge is the highest for the GTL oil and the lowest for the synthetic ester. This rate is considered to be reversely related to branching tendency. With regard to energy efficiency, the energy consumed in the propagation of the shorter side branches does not change the overall severity of a streamer but contributes to the total charge transfer.
Streamers consisting of many short side branches are thus expected to cause a small stopping length per unit of apparent charge. In other words, the same apparent charge reading can associate with different severities of PD in different liquids. The interpretation of PD measurement results should take into account the influence of liquid chemistry.

In divergent AC fields, the space charge effect in the synthetic eater was observed and analysed. Preceding streamers can deposit homo or hetero charges in the liquid, which can alter the electric field distribution in the liquid and influence the propagation of subsequent streamers. A subsequent streamer tends to bypass the trace of previous streamers comprising homo charge, or follow the trace of the previous streamers comprising hetero charge.

**Streamer characteristics of transformer liquids in quasi-uniform AC fields:**

As a result of an increased uniformity of the electric field, a higher increasing rate of stopping length with respect to voltage was recognised. This indicates that streamers will have a stronger ability to propagate when the electric field becomes more uniform. The results obtained with the NP and PNP electrode systems signify the change of dominant breakdown factor from streamer propagation in divergent electric fields to streamer initiation in quasi-uniform fields under AC stress. The streamer shape also varied with electric field uniformity. Streamers have much fewer branches in quasi-uniform fields than in divergent fields, especially in the region near the needle tip.

The suppressed streamer branching tendency in quasi-uniform fields resulted in different correlations between streamer stopping length and apparent charge from those established for divergent field conditions. The stopping length per unit of apparent charge is much higher in quasi-uniform fields than in divergent fields for individual liquids. Therefore, the uniformity of the electric field should be taken into consideration when assessing the severity of PD and it can outweigh the effects of liquid chemistry.
7.3 Further Work

7.3.1 Effects of Liquid Temperature on PD and Streamer Characteristics

Transformer liquids may have different PD characteristics at elevated temperatures [164-166]. In this research, PD measurements were undertaken at room temperature. During the operation of a power transformer, the top oil temperature may be up to 60°C higher than the ambient temperature. The temperature dependence of PD measurements thus needs more research. If the temperature effect is proven to exist, comparisons of PD testing results will only be valid if the tests are carried out at the same temperature. Contrarily, if the temperature effect is negligible, the numerous results obtained in laboratories at different temperatures can be applied directly. Since gaseous processes are involved in streamer development, a change in the liquid temperature may also alter the streamer behaviour. If the changes in streamer physics can be observed and quantified, the experimental results regarding the effects of temperature may be reconciled.

7.3.2 PD and Streamer Characteristics of Transformer Liquids in Quasi-Uniform Electric Fields in Large Gaps

Both the PD and streamer characteristics of all three transformer liquids varied significantly after the electric field uniformity was increased. However, the PDs and streamers that occurred are still considered to be needle-induced, instead of particle- or defect-induced, as happens in reality. In future experiments, attempts should be made to further increase the uniformity of the electric field by reducing the length of the needle protrusion. Since the PDIFs of the three liquids are known for the tip radius of 3 µm, the PDIV measurements can be well estimated by simulating the field enhancement factor for a new electrode configuration. The streamers will have an enhanced propagation ability; therefore, the gap spacing should be enlarged accordingly so that the behaviour of streamers at the propagation stage can be recorded before breakdown happens. The data collected in such large gaps under more uniform electric field conditions will be valuable.
for extrapolation to real scenarios.

7.3.3 PD Measurement using UHF Sensors

The benefits of using UHF sensors have been introduced in Chapter 2. PD measurement in the UHF frequency band is very promising for the online monitoring of power transformers. At present, one major issue that hinders the application of the UHF method is the reconciliation of the measurements generated from the standardised electrical means and from the non-standardised UHF method. Therefore, the experiment setup should be fitted with UHF sensors in the future so as to gain more experience of the links between the PD signals captured in different frequency bands.

7.3.4 Effects of Additives on the Correlations between PD and Streamer Characteristics

In this study, two influential factors of the correlations between PD and streamer characteristics were identified, i.e. liquid chemistry and electric field uniformity. Additives having a different ionisation potential (IP) or electron affinity (EA) from the transformer liquid, e.g. ionisers that have a low IP, and electron scavengers that are highly electronegative, can be added to the samples in future experiments. As a result of the interactions between electronic and gaseous processes, both PD quantities and streamer physics can be influenced by the additives and their correlations may be altered. In that case, the results will help gain a deeper insight into the correlations between PD and streamer characteristics under AC.
Appendix 1: Effects of Contamination on PD Characteristics of Transformer Liquids

Transformer insulating liquids in reality contain many impurities, such as water, particles, acids, etc. Those impurities could trigger discharges [167]. Water is an ageing product of cellulose materials [168]. In some cases, moisture ingress happens when humid air enters the tank or when gaskets are not properly functioning. Particles can originate from the wear and oxidation of metallic parts and cellulose materials and inadequate filtering practices [147]. Acids can be present in liquids as a result of oil and paper ageing [169, 170]. Therefore, a wide range of contaminants are inevitably present in transformer liquids. Impurities have detrimental effects on the dielectric strength of transformer liquids. It will be beneficial to know whether the presence of contamination can alter the PD characteristics of transformer liquids. This section discusses the effects of moisture and cellulose particles by comparing the PD characteristics of clean and contaminated liquid samples.

Liquid samples used in the experiments are prepared through different treatment procedures and are distinguished in three conditions, which are clean, moist and contaminated with dry cellulose particles. Clean samples are filtered and dehydrated at 85°C, 500 Pa (500 mBar). Because of the different water saturation levels, clean samples of Gemini X and Diala S4 ZX I are dried for 48 hours, whereas those of MIDEL 7131 are dried for 72 hours. Moist samples are filtered and then kept in environmental chambers of 50% relative humidity for 60 days. Particle contaminated samples are obtained by adding dried cellulose particles (Cellulose Powder CF11 produced by Whatman plc) to clean samples. The relative humidity of clean and particle contaminated liquid samples is less than 10% at 20°C. That of moist liquid samples is between 40% and 50% at 20°C. Clean and moist liquid samples have a ‘low’ contamination level in accordance with the
designates in [147], whereas particle-contaminated liquid samples have a ‘high’ contamination level. A comparison of the different liquid sample conditions is provided in Table A1-1. All the experiments are carried out at room temperature. Liquid samples contaminated with particles are constantly agitated during the measurements to avoid depositing on the bottom of the test cell or bridging the oil gap. Although part of the particles still settle in the bottom corners of the test cell, the particle content of the sample is consistent before and after each experiment according to the particle counts. 100 ml of particle-contaminated liquid samples contains more than 130,000 particles whose diameter is larger than 5 µm and contains more than 16,000 particles whose diameter is larger than 15 µm (100 ml of filtered samples contains fewer than 1,000 particles whose diameter is larger than 5 µm and fewer than 130 particles whose diameter is larger than 15 µm).

Table A1-1. Typical moisture content and particle count for different sample conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Relative humidity at 20°C</th>
<th>Particle contamination level according to CIGRE TB 157 [147]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>&lt; 10% for Gemini X and Diala S4 ZX-I &lt; 5% for MIDEL 7131</td>
<td>low</td>
</tr>
<tr>
<td>Moist</td>
<td>40 - 50%</td>
<td>low</td>
</tr>
<tr>
<td>Cellulose particle contaminate</td>
<td>&lt; 10% for Gemini X and Diala S4 ZX-I &lt; 5% for MIDEL 7131</td>
<td>high</td>
</tr>
</tbody>
</table>

The test circuit shown in Figure 3.1 is employed, but the streamers and current pulses appearing in the liquid samples are not recorded. At 55 kV, the noise level of the setup is below 12 pC. The changes in the PD characteristics in response to increased moisture content and cellulose particle contamination level are investigated only in divergent fields (with the NP electrode system). When measuring the PDIVs of the contaminated liquid
samples, three gap spacings are used, including 10 mm, 25 mm and 40 mm. When carrying out PD measurements at voltages above PDIV, a gap spacing of 40 mm is used.

**A1.1 Effects of Moisture**

According to Figure A1-1, moist liquid samples have a very similar PDIV to clean ones except that the PDIV of the moist synthetic ester increases slightly. This increase in PDIV will be discussed subsequently with the support of pulse repetition rate measurements. With regard to the PD inception in divergent electric fields, the sharp needle tip is still the primary defect in the liquid samples, outweighing the influence of dissolved water.

PD measurements at higher voltages are undertaken with the NP electrode system at a gap spacing of 40 mm. Figure A1-2 and Figure A1-3 include the PD magnitudes and pulse repetition rates of moist liquid samples in comparison to those of clean ones. The PD magnitudes of the three liquids are almost unchanged for moist samples. So the significance of PD magnitudes in revealing changes in moisture content is limited. However, compared with PD magnitudes, pulse repetition rates appear to be more sensitive to moisture content. Depending on the type of liquid, the pulse repetition rate may either increase or decrease with increased moisture content. The moist samples of the mineral oil and GTL oil exhibit a slightly higher pulse repetition rate. As for the synthetic ester, an obvious decrease in its pulse repetition rate has been observed as a result of increased moisture content at voltages below 35 kV (which is approximately 2 times the PDIV). Since measurements of PDIV can be affected by discharge frequency, the decrease in the pulse repetition rate to a certain degree contributes to the slightly higher PDIV of the moist synthetic ester. The same influence of moisture on the pulse repetition rate of the synthetic ester is previously observed with the needle-to-sphere electrode system [100].
The effects of additives are often predicted and analysed through the changes in the ionisation potential (IP) and availability of free electrons, since they govern impact ionisation and electron avalanche processes [111, 112]. The IP of water is 12.6 eV [171], which is considered not low enough for facilitating impact ionisation through the release of electrons. The high electronegativity of the oxygen atoms in water molecules may play a more influential role in altering the pulse repetition rates of the liquids as a result of electron trapping. Water molecules can form hydrogen bonds and become water clusters in the insulating liquids. Water clusters are more efficient at trapping electrons than water molecules due to the closer proximity between oxygen atoms [96]. As a result, electrons originating from the ionisation of the insulating liquids in the high field region could be trapped within the water clusters. On the one hand, fewer electrons might be available for electron avalanche and impact ionisation. This is probably the key reason for fewer positive discharges triggered in the moist synthetic ester. On the other hand, the trapping of electrons could create anions that are able to enhance the likelihood of electron avalanche in positive half cycles, and this is probably the dominant influential factor for the mineral oil and GTL oil. Whether electron avalanche is suppressed or facilitated may be dependent on moisture concentration. The synthetic ester has a much higher water solubility (over 2000 ppm) than the mineral oil (~55 ppm) and GTL oil (~49 ppm) at room temperature. Hence the same percentage of relative moisture content implies that a
much larger amount of water/water clusters is present in the synthetic ester. Water and water clusters have shown positive EAs (electron affinity) [172-174]. The anions formed can also be ionised when the electric field is sufficiently high and the anions then release electrons and facilitate electron avalanches. This may be the explanation for the comparable pulse repetition rates of the moist and dry synthetic ester samples at high voltages shown in Figure A1-3.

Figure A1-2. Effects of moisture on PD magnitude (NP electrode configuration, gap spacing = 40 mm)

Figure A1-3. Effects of moisture on pulse repetition rate (NP electrode configuration, gap spacing = 40 mm)
A1.2 Effects of Cellulose Particles

The addition of cellulose particles results in a slight reduction of PDIV for the mineral oil and synthetic ester, as shown in Figure A1-4. In contrast, the effect of cellulose particles on the PDIV of the GTL oil is minor. So, in highly divergent electric fields where the needle point is the major defect that triggers discharges, it remains doubtful whether PDIV can be adequately indicative of condition change in terms of particle content.

Cellulose particles play a significant role in determining the dielectric strength of a liquid [175]. According to Figure A1-5 and Figure A1-6, cellulose particles can alter the PD characteristics of the mineral oil and GTL oil. After the addition of cellulose particles, these two liquids have a larger PD magnitude and a larger pulse repetition rate. However, no obvious change in the PD magnitude and pulse repletion rate of the synthetic ester is observed. According to the findings published in [129], when the particle concentration in the mineral oil exceeds a critical value, the discharge number may not increase further.

![Figure A1-4. Effects of cellulose particles on PDIV (NP electrode configuration, gap spacing = 40 mm)](image)

The effects of cellulose particles could be attributed to permittivity mismatch and movement of particles [176]. The dielectric constant of cellulose particles (~4) is higher than the dielectric constants of insulating liquids (~3.2 for the synthetic ester and ~2.2 for...
the mineral oil and GTL oil). At the liquid-particle interfaces, a local field enhancement might exist in the vicinity. In the high field region near the needle tip, this field enhancement experienced by the liquid could ease the initiation of PD. The mineral oil has the lowest dielectric constant and viscosity among the three liquids; therefore it appears to be most vulnerable to the presence of cellulose particles. The synthetic ester has the highest dielectric constant and viscosity and is little affected by cellulose particles.

Figure A1-5. Effects of cellulose particles on PD magnitude (NP electrode configuration, gap spacing = 40 mm)

Figure A1-6. Effects of cellulose particles on pulse repetition rate (NP electrode configuration, gap spacing = 40 mm)
A1.3 Further Work

The effects of moisture and cellulose particles were investigated using the NP electrode system at a gap spacing of 40 mm. With increasing moisture content, the mineral oil and GTL oil produced more discharges, whereas the synthetic ester produced fewer at voltages lower than 35 kV. The mineral oil suffered from more discharges when its particle contamination level was increased. In contrast, the synthetic ester was little affected by the addition of cellulose particles. As the underlying mechanisms of the contamination effects remain unclear, it will be helpful to undertake PD measurements with liquid samples of various intermediate contamination levels and to gather more experimental data. It will be particularly interesting to know if the pulse repetition rate of the synthetic ester will reduce with increasing moisture content in the range of 20% to 40% at room temperature. The effects of liquid condition and electric field uniformity on the PD characteristics of the three liquids are studied as two separate subjects in this research. Considering that transformer liquids in reality are subjected to the combined influence of contamination and uniform electric field, PD measurements should be carried out with contaminated liquid samples in quasi-uniform fields in the future. Correlations exist between PD and streamer characteristics. So the changes in the streamer physics in response to the change of liquid condition will help interpret the PD measurements results of contaminated liquid samples. PD and streamer measurements should thus be conducted simultaneously in future investigations of the contamination effects.
Appendix 2: Experimental Results Obtained with a Needle-to-Sphere Electrode System

Besides water and particles, acids are also present in transformer liquids as a result of oil and paper ageing. Appendix 2 provides the PD measurements obtained with clean, moist and acidic transformer liquid samples. The electrode configuration used is needle-to-sphere. The needle electrodes have a tip radius of 3 µm. The sphere electrode has a diameter of 12.5 mm. The gap spacing between the two electrodes is 50 mm. These dimensions fully comply with the IEC 61294. The test circuit shown in Figure 3-1 is employed, but the streamers and current pulses appearing in the liquid samples are not recorded. At 60 kV, the noise level of the setup is below 12 pC.

The clean and moist transformer liquid samples are prepared using the same procedures as described in Section 3.2.2. To prepare acidic liquid samples, two types of acids are mixed with clean samples, which are stearic acid and formic acid. Stearic acid is a high molecular weight acid (HMA), whereas formic acid is a low molecular weight acid (LMA). HMA contaminated samples are mixtures of 1 g of HMA with 500 ml of clean liquid sample. LMA contaminated samples are mixtures of 0.3 g of HMA with 500 ml of clean liquid sample. Both types of mixtures are agitated at 50°C for 2.5 hours. The typical moisture contents and acidities of clean, moist and acidic liquid samples are given in Table A2-1.

According to the PDIV measurements shown in Figure A2-1, the mineral oil and GTL have similar PDIVs. The synthetic have the lowest PDIV among the three liquids. The presence of moisture, HMA and LMA does not ease PD inception in the divergent fields provided by the needle-to-sphere electrode system. So, under divergent field conditions, the sharp needle tip is the primary defect that triggers PDs.
Table A2-1. Typical moisture content and acidity measurements for clean, moist and acidic transformer liquid samples

<table>
<thead>
<tr>
<th>Condition</th>
<th>Moisture content</th>
<th>Acidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>&lt; 10% for Gemini X and</td>
<td>&lt; 0.01 mg KOH/g for Gemini X and</td>
</tr>
<tr>
<td></td>
<td>Diala S4 ZX-I</td>
<td>Diala S4 ZX-I</td>
</tr>
<tr>
<td></td>
<td>&lt; 5% for MIDEL 7131</td>
<td>&lt; 0.03 mg KOH/g for MIDEL 7131</td>
</tr>
<tr>
<td>Moist</td>
<td>40 - 50%</td>
<td>&lt; 0.01 mg KOH/g for Gemini X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diala S4 ZX-I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 0.03 mg KOH/g for MIDEL 7131</td>
</tr>
<tr>
<td>HMA contaminated</td>
<td>-</td>
<td>0.47 mg KOH/g for Gemini X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.54 mg KOH/g for Diala S4 ZX-I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.45 mg KOH/g for MIDEL 7131</td>
</tr>
<tr>
<td>LMA contaminated</td>
<td>-</td>
<td>0.27 mg KOH/g for Gemini X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32 mg KOH/g for Diala S4 ZX-I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.77 mg KOH/g for MIDEL 7131</td>
</tr>
</tbody>
</table>

Figure A2-1. PDIVs of clean and contaminated transformer liquids
Appendix

With the needle-to-sphere electrode configuration, it is confirmed that the PD magnitudes of the three liquids increase with applied voltage, as shown in Figure A2-2. When the same voltage is applied, the synthetic ester gives the highest PD magnitude among the three liquids and the GTL oil gives the lowest. As shown in Figure A2-3, the pulse repetition rates of the mineral oil and GTL oil increase with applied voltage at below 30 kV. They then tend to level off. In contrast, the pulse repetition rate of the synthetic ester monotonically increases with applied voltage in the tested voltage range. In accordance with the findings discussed in Chapter 4, the pulse repetition rate of the GTL oil is higher than that of the mineral oil but is lower than that of the synthetic ester.

Figure A2-2. Comparisons of the PD magnitude among the three transformer liquids
Figure A2-3. Comparisons of the pulse repetition rate among the three transformer liquids

At voltages above the PDIV, differences in the PD magnitude and pulse repetition rate are observed between clean and contaminated liquid samples. According to Figure A2-4 and Figure A2-5, the PD magnitudes of the moist mineral oil samples and moist GTL oil samples remain almost the same as those of the clean samples. However, in Figure A2-6, the moist synthetic ester has a lower PD magnitude than the clean one at below 36 kV. At above 36 kV, the moist synthetic ester has a higher PD magnitude than the clean one. It indicates that the influence of moisture on PD magnitude may vary with electric field intensity as well as liquid chemistry.

According to Figure A2-7 to Figure A2-9, the pulse repetition rates of all three liquids change with moisture content. The pulse repetition rates of the mineral oil and GTL oil increase with moisture content. Unlike the clean mineral oil and GTL oil samples, the moist ones have a pulse repetition rate that monotonically increase with applied voltage. The pulse repetition rate of the synthetic ester decreases with increasing moisture content. At 50 kV, the moist GTL oil has a comparable pulse repetition rate as the moist synthetic ester.
Figure A2-4. PD magnitudes of the clean and contaminated mineral oil

Figure A2-5. PD magnitudes of the clean and contaminated GTL oil
According to Figure A2-4 to Figure A2-6, the addition of HMA does not change the PD magnitudes of the three liquids. As can be seen from Figure A2-7 to Figure A2-9, the pulse repetition rates of the mineral oil and GTL oil generally increase as a result of the contamination by HMA, whereas the pulse repetition rate of the synthetic ester is little affected.
After the addition of LMA, a decreased PD magnitude is observed at low voltages and an increased PD magnitude is observed at high voltages for all three liquids, as shown in Figure A2-4 to Figure A2-6. The changes in the PD magnitude are relatively more obvious with the GTL oil. The pulse repetition rate of the mineral oil reduces at low
voltages in response to LMA contamination but increases at high voltages, as illustrated in Figure A2-7. In Figure A2-8, the same effect is also seen on the pulse repetition rate of the GTL oil. Figure A2-9 indicates that the LMA-contaminated synthetic ester has a decreased pulse repletion rate compared with the clean one.

Currently, no comprehensive interpretation can be provided for the effects of different contaminants on different PD characteristics for different types of transformer liquids. But the effects of moisture on the pulse repetition rates of the three liquids are found consistent under the needle-to-sphere and needle-to-plane electrode configurations. It is also important to confirm with the needle-to-sphere electrode configuration that pulse repetition rates exhibit a higher sensitivity to contaminants than PD magnitudes.
Appendix 3: List of Publications

Journal Articles:


Conference Papers:


Appendix

References


Appendix


Appendix


Appendix


Appendix


[79] M. Pompili, C. Mazzetti, and R. Bartnikas, "Early stages of negative PD development in dielectric liquids," *IEEE Transactions on Dielectrics and Electrical
Appendix


Appendix


Appendix


[125] O. Lesaint and T. V. Top, "Streamer inception in mineral oil under ac voltage,"


[160] G. Massala and O. Lesaint, "A comparison of negative and positive streamers in


