MICROSECOND AND SUBMICROSECOND IMPULSE BREAKDOWN OF INSULATING LIQUIDS AND LIQUID–POLYMER INTERFACES

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date:

Acknowledgement

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Abstract

From many years now industry has been searching for ways to reduce the environmental impact of operations. One area that has drawn attention within both the power and pulsed power industries is the use of mineral oils within large electrical machines and apparatus. Due to the advantageous characteristics ester-based dielectric fluids offer, such as high biodegradability, high flash and fire points, low toxicity and high availability of raw material these fluids have been cited as a possible replacement for traditional mineral oil in high voltage (HV) power assets and pulsed power machines.

Research has therefore focused on how these new fluids perform under the electrical stress typically experienced during the operation of an AC power transformer. However, the standardised testing regimes used in such research are not completely representative of practical stress experienced by pulsed power apparatus. Pulsed power systems are commonly stressed with high impulsive voltages of non-standard wave-shape. This work addresses this gap in knowledge by providing a systematic study of the breakdown behaviour of ester fluids in an overstressed regime (i.e. breakdown ensured to occur on the rising edge of the impulse), while modelling a scenario more representative of bulk insulation within pulsed power machines; with liquid samples in varying levels of moisture saturation stressed with voltages of both standard and non-standard wave-shape to induce breakdown. To further reflect the practical scenario liquid samples were also tested when in direct contact with polymer dielectrics typically used in power and pulsed power machines.

From the experimental work completed in this thesis it has been shown that both natural ester (Envirotemp FR3) and synthetic ester (MIDEL 7131) fluids offer comparable breakdown performance to mineral oil (Shell Diala S4) when used as a bulk insulating medium as well as when paired with practical polymer dielectrics as part of a liquid-polymer composite insulating system when stressed with both standard and non-standard voltage impulses. These findings will provide important data and information for researchers, operators and designers of high voltage power and pulsed power apparatus, facilitating better understand of the dielectric performance of environmentally friendly insulating liquids and leading to increased confidence in their implementation within large electrical machines.

List of Acronyms

AC	Alternating Current
CI	Confidence Interval
CPF	Cumulative Probability Function
DC	Direct Current
EDD	Electric Discharge Drilling
FEM	Finite Element Modelling
GND	Ground
HDPE	High Density Polyethylene
HV	High Voltage
HVDC	High Voltage Direct Current
KS	Kolmogorov-Smirnov
PMMA	Polymethyl-methacrylate
PCB	Polychlorinated Biphenyl
PTFE	Polytetrafluoroethylene
RH	Relative Humidity
V-T	Volt–Time

Publications

Journal paper

- C. Williamson et al., "Impulsive Breakdown of Mineral Oil and Natural and Synthetic Ester Liquids When Containing Varying Levels of Moisture," in IEEE Transactions on Plasma Science, vol. 49, no. 1, pp. 466-475, Jan. 2021, doi: 10.1109/TPS.2020.3044133.

Conference papers

- C. Williamson et al., "The Effect of Impulse Rise–Time on the Breakdown of Composite Ester–Polymer Insulation," In: 2020 Euro-Asian Pulsed Power conference, 2021, Biarritz, France.

- C. Williamson et al., "Breakdown of Composite Ester-Polymer Insulation Under Lightning Impulse Stress," 2020 IEEE International Conference on Plasma Science (ICOPS), Singapore, 2020, pp. 49-49, doi: 10.1109/ICOPS37625.2020.9717521.

- C. Williamson et al., "Investigation of Impulsive Breakdown of Interfaces Formed by Ester Insulating Liquids and Solid Dielectrics," 2019 IEEE Pulsed Power & Plasma Science (PPPS), Orlando, Florida, 2019, pp. 1-4, doi: 10.1109/PPPS34859.2019.9009766.

- C. Williamson et al., "Breakdown Characteristics of Natural and Synthetic Ester Liquids When Containing Varying Levels of Moisture," 2019 IEEE Pulsed Power & Plasma Science (PPPS), Orlando Florida, 2019, pp. 1-6, doi: 10.1109/PPPS34859.2019.9009857.

Contents

Chapter 1 – Introduction

1.1. Background

In recent decades there has been a paradigm shift in the attitudes towards the environmental impact of industrial, commercial and domestic operations. These behaviours are seen at a governmental level with the inception of groundbreaking climate change legislation like the Paris climate agreement signed in 2015 [1]. Such statutes have resulted in an increased responsibility for industry to mitigate environmental impact associated with their operations. In response to this, both the power and pulsed power industries have begun actively searching for methods to lessen operational environmental impact. One such area which poses a possible environmental hazard is the use of toxic naphthenic-based insulating fluids within large electrical machines; such as power transformers and pulsed power apparatus. The power industry has already taken steps to mitigate any possible environmental impact which may result from a large transformer failure; with the deployment of electrical distribution and power transformers utilising environmentally friendly insulating fluids (natural and synthetic esters) in places of conventional naphthenic mineral oil [2]-[4]. These natural ester insulating fluids, as well as their synthetic counterparts, have been shown to offer a tangible alternative to the use of conventional mineral oils for most insulating applications [5], [6]; attributed to the comparability which exists between the dielectric characteristics of these ester fluids and the naphthenic liquid they are proposed to replace. These alternative insulating fluids also offer a number of additional performance benefits as compared to naphthenic liquid; such as an improved safety profile due to the reduced combustibility of ester fluids and enhanced environmental performance as a consequence of the high biodegradability and low toxicity of these liquids. Dielectrics liquids produced from such natural sources will also allow an increase in availability of raw materials given the abundance of ester feedstock. Implementation of ester insulating liquid in place of naphthenic fluids would also facilitate the realisation of operational improvements as a consequence of the increased ability ester fluids possess to accommodate moisture ingress. This will prove highly advantageous given the detrimental affect water content is seen to have on the breakdown voltage of conventional mineral oil [7], [8].

As aforementioned, the use of ester-based dielectric fluid is not new, both natural and synthetic ester liquids have been utilised within insulating applications for decades. Consequently, the behaviour of these environmentally friendly insulating fluids under AC stress is well documented [9]-[12]. Moreover, as these fluids have become more common within large power and distribution transformers [2]-[4] understanding of their dielectric behaviour under standard lightning impulse stress has also been extensively researched [13]-[21]. Each of these testing methods yield different information; with AC stress relating to contamination affects, while impulse testing will provide information on the intrinsic breakdown behaviour of the examined liquid. Consequently, AC stress tests are typically utilised to evaluate the influence relative moisture content of the fluid has on its dielectric strength [7], [8] with researchers, almost universally, reporting a reduction in dielectric strength as relative moisture content is increased. Although as these tests are normally conducted under quasi-uniform field conditions no consideration is made to how increased field divergence may affect any observed reduction in dielectric capability. Moreover, there is a lack of published research discussing how impulse breakdown performance is affected when the examined fluid is in a heightened state of relative humidity.

1.2. Main objectives and overview of research work

The main focus of this study is the systematic investigation of the impulsive breakdown characteristics of three different categories of liquid insulators: natural ester fluid (Envirotemp FR3), synthetic ester fluid (MIDEL 7131) and mineral oil (Shell Diala S4). Significant research efforts have led to characterisation of breakdown behaviour of different insulating liquids stressed with power frequency AC stress or negative standard lightning HV impulses; however, the breakdown behaviour of insulating liquids is not fully understood when these liquids are stressed with HV impulses of both polarities with rise-time shorter or longer than 1.2μs. The present work is addressing this knowledge gap, and presents the systematic investigation of the breakdown behaviour of these selected insulating liquids stressed with the standard lightning impulse (rise-time 1.2μs) as well as HV impulses with shorter and longer rise-times (0.4μs and 7μs respectively).

The research presented in this thesis also involved a comprehensive study of the effect relative moisture content of the fluid has on the impulsive breakdown characteristics of both natural and synthetic ester fluids as well as conventional mineral oil. Within the study three discrete states of relative humidity were evaluated; ‘As Received’ ~10%, ‘Ambient’ ~35% and ‘Elevated’ >70%. As aforementioned, there is a lack of published literature pertaining to how alterations in the wave-front time may affect the dielectric strength of ester fluids. This relationship is well known, and documented, within the breakdown of mineral oils and can be seen in the derived Volt-Time (V-T) curves for these liquids. Information on the V-T characteristics of a dielectric fluid is important for their use within pulsed power apparatus as these machines are commonly stressed with impulses possessing nominal parameters (rise-time, fall-time) which differ greatly from the standard lightning impulse. Given that such curves do not exist at this time for ester-based insulating fluids, a comprehensive investigation was conducted to study the effect of rise-time on the breakdown strength of these fluids.

Three independent wave-front times were used in the present study with rise-time of 0.4μs, 1.2μs (standard lightning waveform) and 7μs. Use of such a range of wave-front times allows for V-T characteristics to be derived for both the bulk performance of ester fluids and when acting as part of a liquid-polymer composite system. Moreover, as the V-T curves published within literature that relate to the performance of mineral oil were developed under uniform field conditions it is important to evaluate how parameters will change when under a highly divergent field. This facilitated the identification of any dissimilarities in the behaviour of mineral oil and ester fluids as well as increasing understanding of how these dielectric liquids behave under highly asymmetric field conditions.

Another novel aspect of the present work includes a comprehensive investigation of the breakdown behaviour of solid-liquid interfaces formed by the selected insulting liquids and commonly used solid polymer insulators, Nylon 6,6, PMMA, TORLON and DELRIN. To this date, to the best of the author knowledge, no systematic studies of the breakdown behaviour of polymer-natural ester, synthetic ester and mineral oil interfaces stressed with HV impulses with different waveforms and polarities have been conducted, although such information is critically important for design of high voltage liquid-insulated power and especially pulsed power systems. This thesis is aimed at filling this gap in the current knowledge of the impulsive breakdown behaviour of solid polymer-insulating liquid interfaces. To achieve this, the breakdown performance of ester fluids when acting as part of a liquid-solid insulating system was investigated. Research in this area has historically focused on the use of Kraft paper as the solid medium; due to its predominance as an insulator for transformer windings. Studies of this nature will however not yield information on how these fluids will behave when in operation with polymer dielectrics. Furthermore, as most published research relates to the performance of liquid-solid insulating systems when stressed with AC or lightning impulse voltage little is known of how non-standard voltage stress may affect the dielectric capabilities of the hybrid ester-polymer system. To overcome this lack of knowledge an investigation was conducted where liquid-solid insulating systems utilising ester fluid and polymer dielectrics were stressed with the same aforementioned impulses used in the bulk breakdown study (0.4µs, 1.2µs and 7µs), with the obtained results compared to the breakdown of mineral oil-solid insulation tested under the same conditions. This will aim to identify what influence the specific type of polymer has on insulating capabilities of the system as well as documenting how impulse parameters can affect breakdown of the composite system. This will prove to be of great use to designers of electrical machines as this information can be used in the coordination of insulation as to reduce the likelihood of catastrophic failure through bulk breakdown of polymer supporting structures.

1.3. Outline of thesis

A brief overview of the content of this thesis is provided in the following section. In this thesis the same experimental and analytical methodologies were used for investigation of the selected liquids in order to compare their breakdown performance at different conditions. Due to this systematic approach to the analysis of obtained experimental data (as fully explained in Section 3.6.1) Chapters 4 through 6 take a similar format.

Chapter 1 – Introduction

This chapter provides information on the motivating factors behind the research project as well as outlining the main research tasks conducted. The Chapter concludes with the provision of an outline of the content of the entire thesis.

Chapter 2 – Literature review

Within Chapter 2 the key findings from a comprehensive literature review into the breakdown of liquid dielectrics as well as liquid-solid composite insulation are presented. The main purpose, and common types, of dielectric liquids used within electric machines is discussed along with the key operational parameters of these fluids. A comprehensive review of the breakdown of liquid dielectrics, and liquid-solid composite insulation, is provided; extending to breakdown mechanisms experienced under AC and impulse voltage stress, development of breakdown streamers and the factors that influence their formulation and growth within dielectric fluids, and the effect relative moisture content can have on the breakdown of liquid dielectrics. The chapter concludes with a review of the current use of ester-based dielectric liquids within industry.

Chapter 3 - Experimental setup, sample conditioning and testing methodologies

The third chapter of the thesis is dedicated to the description of the experimental system and testing methodologies applied throughout the bulk liquid and liquid-solid interfacial breakdown experimentation. A comprehensive account is given of all equipment used within the laboratory investigation; including the impulse generator topologies used, individual test cell designs for both the bulk liquid and liquid-solid interfacial breakdown studies, as well as information on the diagnostic systems employed to collect experimental data and all other auxiliary equipment utilised. Also included within Chapter 3 is a description of how both liquid and solid samples were prepared for use within the experimental studies; this extended to the humidification and degassing of dielectric fluids as well as the manufacture and surface treatment of the polymer materials used. The chapter ends with an outline of the testing and analytical methodologies implemented for the conducting of experiments and the treatment of obtained data respectively.

Chapter 4 - Lightning impulse breakdown of insulating fluids

The first of the chapters focused on the presentation and analysis of experimental data, Chapter 4 provides the breakdown voltage and associated time to breakdown of the three dielectric fluids (mineral oil, synthetic ester and natural ester) when stressed with lightning impulse voltage. All raw breakdown data obtained from the stressing of the individual fluid samples with positive and negative impulse when at three chosen levels of relative humidity (‘As Received’, ‘Ambient humidity’ and ‘Elevated humidity’) is presented. The positive and negative breakdown parameters (breakdown voltage and time to breakdown) of each fluid in a given state of relative humidity are discussed in insolation, followed by a comparison and synopsis of the performance of all three fluids for a specific level of relative humidity. This format is repeated until the data collected for the fluids in the three separate states of relative humidity has been presented and discussed. The chapter is concluded with a summary and analytical discussion of the performance of all three liquids in the varying states of relative humidity when stressed with lightning impulse voltage.

Chapter 5 – Breakdown of insulating fluids with impulses of 7µs rise-time

This chapter is devoted to the provision of experimental data pertaining to the breakdown of the chosen dielectric liquids when in the three discrete states of relative humidity and stressed with impulses longer than the standard lightning impulse. The resulted presented and discussed within this chapter were obtained when the dielectric liquids were placed under microsecond impulse voltage (rise-time 7µs) with both positive and negative impulses used. The format of the chapter mirrors that of the previous (Chapter 4) with a given fluid in a single state of relative humidity discussed in insolation before being compared to the other two liquids at the same level of relative humidity. Once more, the Chapter concludes with a summary and analytical discussion of the breakdown performance of the three liquids in all states of relative humidity.

Chapter 6 – Breakdown of insulating fluids with impulses of 0.4µs rise-time

This chapter is focused on the bulk breakdown performance of the chosen dielectric liquids, it is used to present and discuss the data obtained when the insulating fluids were stressed with impulses shorter than the standard lightning impulse. Data is provided on the breakdown of the three fluids in each of the chosen states of relative humidity when exposed to nanosecond impulse voltages (rise-time 0.4µs) of both positive and negative polarity. As with the other chapters discussing bulk breakdown of the insulating fluids (Chapters 5 & 6), the performance of a given liquid in a specific state of relative humidity is analysed in isolation, with a summary and comparative analysis of the behaviour of all fluids when at a particular level of relative humidity provided. Again, the chapter ends with a synopsis and analytical discussion of the breakdown performance of the dielectric liquids at all three levels of relative humidity.

Chapter 7 - Breakdown of liquid-solid composite insulation

This chapter provides and discusses experimental data pertaining to the breakdown of liquid-solid composite insulating systems consisting of the dielectric fluids (mineral oil, synthetic ester and natural ester) and practical polymer materials (Nylon 6,6, PMMA, TORLON and DELRIN) which are currently used, or proposed to be used, with power and pulsed power apparatus. The composite insulating systems were subjected to three discrete impulse waveforms, identical to those used in the bulk breakdown studies (0.4µs, 1.2/50µs lightning and 7µs), of both positive and negative polarity. The measured breakdown parameters (breakdown voltage and associated time to breakdown) of composite systems using a specific dielectric fluid when exposed to a given impulse shape (rise-time) are discussed in isolation. Once all data for a given waveform has been presented a comparative analysis of the mineral oil and ester-based composite systems is provided; with this format repeated for the three discrete voltage impulses. Conclusion of Chapter 7 comes in the form of a summary and comparative discussion of the breakdown performance of the mineral oil and ester-based composite insulating system under all investigated wave-shapes.

Chapter 8 – Conclusions and further work

The final chapter of the thesis is used to summarise the research project, main findings from the experimental work conducted and major contributions made in the completion of the work. Indication is also provided as to the possibility of further study into key areas unable to be investigated during the timescale of the current project.

Chapter 2 – Literature review

2.1. Introduction

Within large electrical machines liquid dielectrics are commonly implemented to provide volume insulation as well as facilitating the cooling of the equipment. Currently the power and pulsed power industries rely on mineral oil as an insulating liquid due to its desirable properties in terms of high dielectric strength and good thermal conductivity. However, in recent years additional pressure has been placed on industry to reduce the environmental impact associated with the use of mineral oil due to the possible contamination of soil and water sources that can result from leakages or spillage, as well as risk to maintenance staff through contact with, or inhalation of, the fluid. This has resulted in the power and pulsed power industries actively searching for viable replacements for naphthenic mineral oil, with ester-based dielectric fluid shown to be a possible substitute for these non-biodegradable dielectric liquids. In order to fully substantiate the ability of ester fluids to replace mineral oil in large electrical machines and pulsed power apparatus better understanding of their breakdown characteristics is required.

This chapter is focused on the presentation and discussion of the key information pertaining to the breakdown of dielectric liquids. First, an overview of both liquid and liquid-solid insulating systems is provided as well as a review of the physical and electrical properties of mineral oil and ester-based dielectric fluids. While there is no universal agreement within the research community of the breakdown mechanisms of dielectric liquids the main theories, such as the development of streamers, are presented and discussed. Previous studies conducted into the breakdown of mineral oil and ester-based dielectrics under impulse voltage as well as liquid-polymer composite insulation are reviewed, with discussion of the main factors influencing breakdown behaviour. The chapter is concluded with an evaluation of the current use of ester fluids within large electrical machines.

2.2. Insulating systems

The electrical insulating system is an integral part of any high voltage machine or system. High voltage insulation can take one of four forms (vacuum, gas, liquid or solid) and is used predominately to block the flow of electrical current between two conductors. However, depending on the specific insulating medium utilised it may also be required to perform other tasks within the electrical machine or apparatus; for example, facilitating machine cooling as is common when liquid dielectrics are used or act as a dielectric barrier as is the case for solid insulating materials. The pairing of two or more dielectric materials to create a composite insulating system is also a common practice in the design of electrical machines; this can be seen within transformers where solid insulation (in the form of Kraft paper) is in direct contact with liquid dielectric used as the volume insulator and cooling medium. Each dielectric material, or dielectric pairing, can offer specific advantages but also has disadvantageous aspects; with these factors considered during the insulation selection phase of machine/system design.

2.2.1. Insulating liquids

Insulating liquids are the most common dielectric used within large electrical machines and pulsed power apparatus. This can be attributed to their high dielectric strength (usually in excess of 60kV/mm) as well as their abilities to recover their dielectric properties after breakdown [22]. A comprehensive overview of the key properties required of any dielectric liquid was provided by Ushakov in [22], stating that any dielectric fluid may only be suitable for use within large electrical equipment when it satisfies the following criteria: 1) it must have high dielectric strength, 2) possess high relative permittivity, 3) be of low electrical conductivity, 4) show low rates of decomposition during electrical discharge, and 5) demonstrate fast restoration of its dielectric properties following electrical breakdown. Both mineral oil and ester-based dielectric fluids have been experimentally shown to meet the aforementioned critical criteria [5], [6].

Further to those criteria mentioned above there are other important operational parameters associated with dielectric liquids such as: dissipation factor (tan δ loss), thermal conductivity, relative moisture saturation level, liquid viscosity, pour point, flash and fire points, oxidation stability, level of biodegradability and toxicity. Each of these parameters must be considered during the selection of a particular dielectric liquid for use with large electrical machines and pulsed power apparatus. Each of these key operational characteristics will be further explained below:

- Dissipation factor; also known as “tan δ” or the “dielectric loss factor”, is a non-destructive testing method used to quantify the energy converted within a material to heat losses when the material is exposed to an external electric field. Any material which exhibits a high loss angle is therefore not suitable for use as a dielectric material due to the increased likelihood of thermal breakdown.
- Thermal conductivity; this is an important parameter given the dual requirement of dielectric fluids to act both as an insulator and means of conducting heat away from critical parts of the machine. Measured values for this parameter are observed to reduce with increases in external temperature but average ~0.129W/m^2/K for mineral oil and ~0.179 W/m^2/K for natural ester fluid between 25°C – 80°C [23].
- Relative moisture saturation; more commonly known as “relative humidity” this parameter describes the water content of a fluid as compared with its ultimate saturation limit. It must be said that this saturation limit, given in ppm, will vary with fluid temperature and this must be accounted for when deriving the relative humidity. Typical water saturation levels for mineral will be approximately 70ppm [24] with this limit much higher for natural and synthetic ester fluids, ~1100ppm [25] and ~2600ppm [26] respectively, when the fluid temperature is ~20°C. In the case of insulating liquids, the level of water must be kept as low as practically possible given the known detrimental effects of water on breakdown strength [27].
- Liquid viscosity; this parameter denotes the ability of a fluid to resist flow and thus must be of a low value for any insulating liquid given the requirement of the fluid to facilitate adequate cooling within large electrical machines. This is of concern when implementing ester fluids as a replacement for mineral oils given their increased viscosity; ~70mm^2/s for both natural and synthetic ester fluids [28], [29] as compared with ~22mm^2/s for conventional mineral oil [29] when at 20°C.

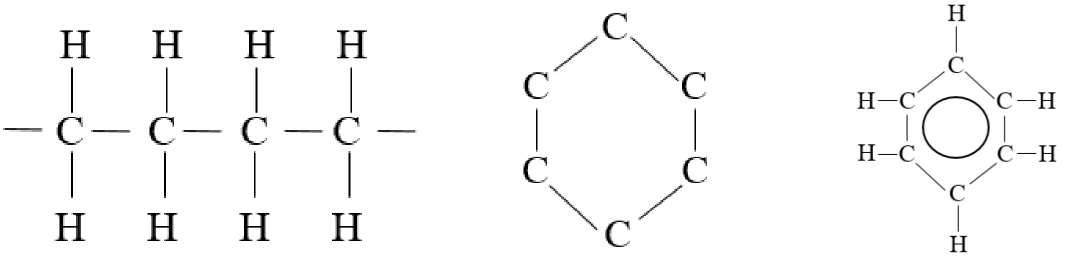
- Pour point; represents the lowest possible temperature at which a fluid may still flow. This is of particular importance when the insulating fluid will be exposed to an environment where expected temperatures are extremely low. The pour points for both natural and synthetic ester fluids are considerably higher than mineral insulating oils; -14°C [30], -18°C [30] and -50°C [31], respectively.
- Flash and fire points; used to evaluate the combustibility of an insulating liquid this is an important parameter in establishing the safety of a fluid. The flash point of a liquid is defined as the lowest temperature at which a flammable mixture of the fluid and air will occur. With the fire point used to describe the temperature at which the flammable mixture will burn when ignited for a duration of five seconds or more. Ester fluids show advantageous properties in this area as they possess much higher flash and fire points than conventional mineral oils; with the fire point of both natural and synthetic fluids exceeding 300°C [25], [26] but as low as 170°C for mineral oils [24].
- Oxidation stability; describing the polymerisation of a fluid when exposed to oxygen, this parameter can be used to indicate the expected increase in acidity of the liquid or the amount of polymeric products generated, in the case of ester fluids, or ‘sledge’ when referring to mineral oils. The degree of oxidisation experienced by an insulating fluid is extremely important as it is associated with the expected lifetime of the fluid and can directly influence the operational stability of the insulating system.
- Level of biodegradability; this reflects the ability of a fluid to be broken down through naturally occurring processes. There are two main criteria which must be satisfied in order for a fluid to be described as biodegradable: 1) it must experience rapid decline in three key areas: dissolved organic carbon (70% reduction), theoretical carbon dioxide (60% reduction) and theoretical oxygen demand (60% reduction), 2) the reduction in these parameters must occur within a ten-day period within a twenty-eight-day timeframe [32].
- Toxicity; the toxicity of a given insulating liquid describes how damaging exposure to this fluid is for living organic matter. This is of great importance when evaluating the expected effects of

a leakage or spill of the fluid to the surrounding environment. Ester fluids have been shown to possess a much lower level of toxicity to that of conventional mineral oils [33].

The work described in this thesis pertains to the study of three different insulating fluids, namely one conventional mineral oil and two ester fluids (one synthetic and one natural). Therefore, a comprehensive overview of these chosen dielectric fluids will now be provided.

2.2.1.1. Mineral oil

Mineral oils are the most common dielectric fluid currently used within large electrical machines, high voltage switchgear, HVDC cables and pulsed power apparatus. These oils are produced as a by-product of the petroleum distillation process and consist of a complex mixture of hydrocarbon molecules. The individual constituent molecules of mineral oils can be subdivided into three main groups; paraffinic, naphthenic and aromatics [34], each with their own molecular structure and influence on the dielectric properties of the fluid. A brief description of each of these three main molecules, as well as their basic structures, have been provided below.



(a) (b) (c)

Figure 2-1; *Compounds found within mineral oil; (a) Paraffinic; (b) Naphthenic; (c) aromatics.*

Paraffinic; these molecules will take the form of either straight or branched structures (Figure 2-1a). In the case of paraffinic molecules, it is those of straight morphology which have the biggest influence on mineral oil characteristics and should be limited where possible. This is due to the tendency of these molecules to produce waxes and sludge when exposed to oxygen [34].

Naphthenic; consisting of a carbon ring structure (Figure 2-1b), these molecules provide good low temperature stability resulting in improved viscosity of the oil when exposed to cold environments. This property of naphthenic molecules also results in an increased life expectancy of the oil.

Aromatics; similar to naphthenes in their morphology, as they too are formed of a carbon ring, however unlike naphthenic molecules aromatics also contain a single or double bond (Figure 2-1c) resulting in completely different physical and chemical properties. Aromatics are the single most important and influential molecule in mineral oil as they have a direct effect on the dielectric characteristics of the fluid. Subdivided into mono and poly aromatics, each has a contrasting influence on the properties of the mineral oil. Presence of mono-aromatics provides good gas absorption while also remaining stable under oxidation [34]. Poly-aromatics however have been shown to increase the acceleration of both positive and negative breakdown streamers in mineral oil and also greatly reduce negative breakdown strength of the fluid [35].

While the exact composition of a particular mineral oil is not provided by their manufacturer in the supporting documentation, there is a means of classifying the fluid based on the concentration of these fundamental constituents. This is usually achieved by simply evaluating the dominant hydrocarbon present within the fluid. For a mineral oil to be deemed ‘naphthenic’ it must consist of <50% carbon atoms while fluids made up of ≥50% carbon atoms will be termed ‘paraffinic’ [36].

Mineral oil insulating fluids offer a number of advantages, some intrinsic to all dielectric fluids such as ability to mould to any volume, excellent recoverability of dielectric properties after breakdown and dual operation as an insulating and cooling medium, while some are unique to the fluid such as its minimal cost and low viscosity and excellent pour point. These fluids however are not without drawbacks particularly with respect to fire safety and environmentally concerns associated with their low flash and fire points, non-biodegradability and inherent toxicity.

2.2.1.2. Synthetic ester fluid

First developed in the mid-1970s [2] synthetic ester fluids are manufactured from organic alcohols and acids. Their molecular structure (Figure 2-2) typically consists of between two and four saturated acids, such as carboxylic acid as this allows for the chaining of multiple acid groups, which is then bonded to a polyol tera-alcohol spinal structure. Creation of such a molecular structure ensures excellent chemical stability [37]. Production of these synthetic dielectric liquids is now governed by IEC 61099 [38].

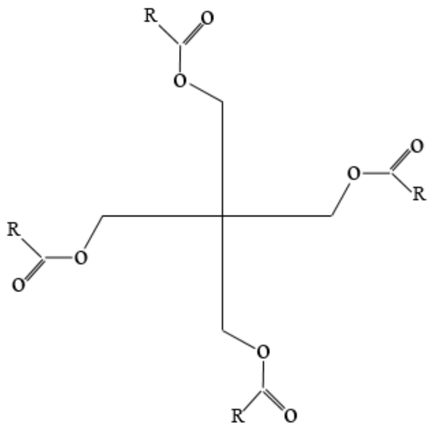


Figure 2-2; *Structure of synthetic ester molecules*

There are numerous types of synthetic ester fluid used, or proposed to be used, within electrical equipment. They can however be broadly categorised into two groups: Phosphoric esters and Tetraesters. The first of these, phosphoric esters, are not widely used due to concerns about their environmental impact due to the presence of phosphoric acid within their molecular structure [39]. Tetraesters, or ‘pentaerythrotol esters’, are much more extensively utilised due to their environmentally friendly nature and thus have grown to be the predominate formulation of synthetic ester fluid found in electrical equipment. This type of synthetic ester fluid has been implemented in a wide range of electrical equipment from transformers to HV switchgear [40] and has even been shown to extend the expected lifetime of electrical transformers through its ability to slow cellulose degradation [41].

Synthetic ester dielectric liquids also offer good oxidation and thermal stability [42] as well as increased levels of fire safety and improved biodegradability as compared with mineral oils as they do not produce dioxins when exposed to fire [43]. Further to this, synthetic ester fluids also possess other advantageous attributes such as an increased ability to absorb moisture and higher relative permittivity than conventional mineral oils.

2.2.1.3. Natural ester fluid

Dielectric liquids derived from natural esters have been the subject of substantial research since the beginning of the 1990s [2] mainly due to their environmentally friendly attributes. This type of dielectric fluid is produced from naturally occurring oils from the seeds of crops such as rapeseed, soy, coconut, palm or sunflower [39]. The structure of all natural esters, respective of source seed, share a common form with three fatty acids, both saturated and unsaturated, bonded to a glycerol backbone (Figure 2-3).

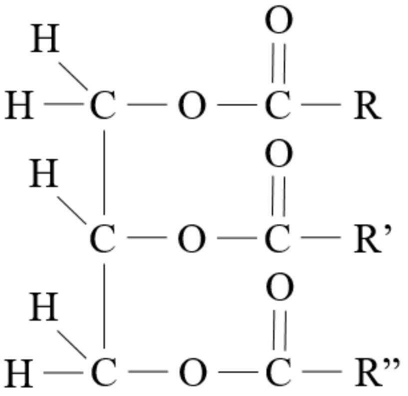


Figure 2-3; Structure of natural ester molecules

The specific fatty acids, be they saturated, mono-unsaturated or poly-unsaturated, which exist in the structure of the natural ester molecules will have a direct effect on the characteristics of the fluid. The types of fatty acids present in, as well as their influence on, the most common natural ester dielectric fluids, those derived from soybean, sunflower, rapeseed and canola, are summarised in Table 2-1.

Table 2-1; Overview of fatty acid content of commonly used sources of natural ester fluid

Oil	Saturated fatty acids		Unsaturated fatty acids			Comments
	Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2	Alpha Linoleic C18:3	
Soybean	11%	4%	24%	54%	7%	Mildly susceptible to oxidation. High viscosity
Sunflower	7%	5%	19%	68%	1%	Poor oxidation stability.
Rapeseed	5%	2%	61%	20%	12%	Reasonable oxidation stability, pour point and viscosity
Canola	4%	2%	62%	22%	10%	Reasonable oxidation stability, pour point and viscosity

As is apparent from the information presented in Table 2-1, the specific molecular structure of natural ester dielectric fluids will have a direct influence on its suitability as an insulating fluid. Natural ester fluids with high concentrations of saturated fatty acids will have much improved oxidation stability though at the expense of incurring a higher viscosity and pour point, conversely natural ester fluids which contain a high level of poly-unsaturated (bi and tri) acids will offer lower viscosity and pour point but will exhibit poor oxidation stability. It is therefore of great importance when selecting a natural ester fluid for a given insulating application that its composition, specifically the presence of these particular fatty acids, is taken into account.

Much like synthetic ester fluids, natural ester dielectrics offer a high level of biodegradability, negligible toxicity and much higher flash and fire points than conventional mineral-based transformer oils. These natural fluids however do possess some disadvantageous attributes such as relatively high loss angle (dissipation factor), increased viscosity compared to both synthetic ester and mineral oil, as well as a higher pour point than these two liquids, and, depending on its molecular structure, very poor oxidation stability. These attributes have resulted in natural ester dielectric fluids only being employed as capacitor dielectrics for many years [44]. However, in recent decades the use of these naturally derived fluids has become more prevalent with natural ester fluids now present within a number of distribution level transformers [2].

2.2.2. Composite liquid-solid insulation systems

It is common practice within large electrical machines and apparatus to combine two or more forms of dielectric to create a composite insulation system. This is most often seen in the case of electrical transformers where both liquid and solid insulating materials are used; the former to provide volume insulation and act as a coolant, while the latter is used as insulation for conductive metal parts of the transformer such as its windings [45]. In such composite systems the liquid insulating medium will typically be mineral-based transformer oil, however ester fluids have also been used in recent decades [2], with the solid dielectric taking the form of either Kraft paper or pressboard. These liquid-paper/pressboard systems are the most prevalent form of composite insulation used within the power industry however this is not the case within other industries utilising large electrical machines and equipment; for example, the pulsed power industry. Pulsed power technology relies heavily on electrical apparatus such as capacitors which utilise composite insulation in the form of thin polymer films typically immersed in castor oil [46]. Further to this, complex pulsed power machines, typically those used to generate high-powered X-rays [47] will require solid polymer insulation to provide mechanical support to internal structures of the machine and/or to facilitate separation between two forms of liquid insulation within the machine, while using liquid dielectrics as a volume insulator and cooling medium. Examples of polymers used in the supporting structures of large pulsed power machines include Nylon 6,6, Polytetrafluoroethylene (PTFE), Polyethylene and Polymethyl-methacrylate (PMMA).

Irrespective of the specific practical application the composite insulating system may be used for, a number of key design considerations can be thought of as common to all forms of composite system. The first of these is to ensure the two insulating materials can remain chemically stable when in contact and under sustained thermal, mechanical and electrical stress. Both materials must have close to equal values of relative permittivity in order to mitigate the enhancement of electrical fields occurring at any interface between the two materials. In the case of liquid-solid composite systems care must be taken in the selection of the dielectric materials to ensure no impurities present in the solid medium may permeate into the liquid which may result in a deterioration of the dielectric properties of the liquid.

2.3. Breakdown mechanisms in dielectric liquids

The breakdown of liquid dielectrics under impulse voltage stress has been extensively investigated by a number of individual researchers over the decades resulting in a large body of work [48]-[69] pertaining to the possible mechanisms and phenomena responsible. Despite these extensive research efforts, no unified theory exists in relation to the mechanisms which result in the breakdown of dielectric liquids. This can be attributed to a number of factors such as the complex molecular structure of practical liquid dielectrics, the existence of contamination (dust, fibres, or particulates) within such liquids and the presence of unspecified additives within practical fluids. That said, some consensus does exist in that the main mechanisms responsible for the breakdown of dielectric liquids can be described by one of three predominate theories; the suspended particle theory, the bubble formation theory and the ionisation (streamer) theory. Each of these theories will be discussed herein with reference, where possible, made to studies relating to the aforementioned dielectric fluids investigated within the work presented in this thesis (mineral oil, synthetic ester and natural ester).

2.3.1. Effect of suspended particles

The presence of varying forms of contamination, such as particulates, within the dielectric liquid have been shown to have a detrimental effect on breakdown strength of the fluid [48], [49]. This effect was demonstrated in [50] to exert the greatest influence on breakdown strength under AC/DC voltage stress due to the significant amount of time available for particles to become polarised dipoles by the externally applied electric field (Figure 2-4b).

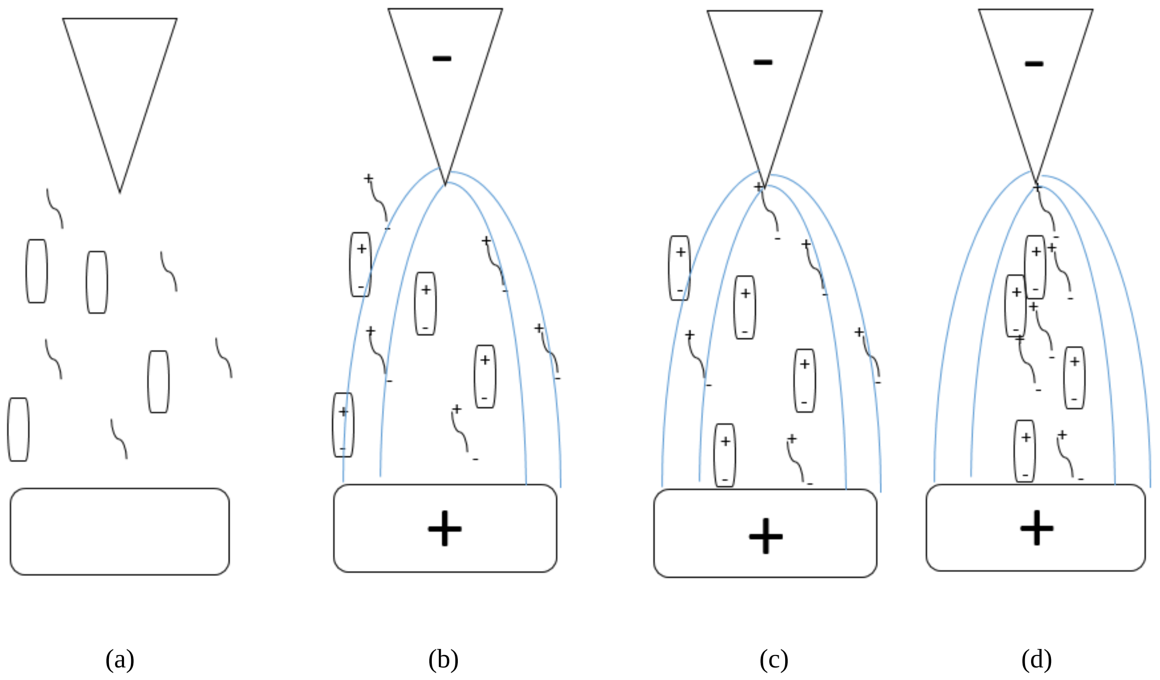


Figure 2-4; *Overview of the effect of suspended particles; (a) particles and fibres present in fluid in the absence of electric field excitation; (b) external field polarises particles and they begin to migrate; (c) particles begin to group together at anode and cathode as well within centre of the inter-electrode gap; (d) the inter-electrode gap is bridge and breakdown occurs. In the depiction rectangles represent solid particulates such as metals and wavy lines show particulates such as cellulose (paper) fragments.*

Under such AC/DC energisation two possible situations may occur; polarised particles located close to the electrodes will enhance the field through pseudo-extension of the electrode into the fluid gap [50]

(Figure 2-4c) or a conductive bridge between electrodes will be formed of particles which have been concentrated within the centre of the inter-electrode gap [49] (Figure 2-4d). When in the presence of a divergent electric field, as shown in Figure 2-4, these two processes are dependent on the relative permittivity of both the particles and the dielectric liquid. In the case where the permittivity of particulates is greater than that of the liquid, particles will behave as described above, conversely when particulate permittivity is below that of the liquid the field excitation will result in the dispersal of the particles away from the electrodes and inter-electrode space. It must be said however that these particle effects are shown in [51] to have negligible influence on breakdown strength when the liquid is stressed with short duration impulse voltage; attributed to the insufficient time for any polarised particles to travel within the inter-electrode gap. The presence of particulates has however been shown in [52] to exert some influence on breakdown under impulse conditions, in this work the authors suggest that when liquids are stressed with impulses of ~1μs impurities may be the catalyst for the inception of bubbles.

2.3.2. Formulation of gas cavities (bubbles)

This breakdown mechanism occurs as a result of the creation of a low-density region within the volume of the dielectric liquid. This region commonly manifests as a vapour bubble, which forms as a consequence of local Joule heating in the liquid or potentially due to significant electromechanical forces when the liquid is stressed with a high electric field. Sharburgh and Watson in [53], [54] present evidence that when a liquid is stressed with an intense local electric field a bubble will form on asperities on the cathode (Figure 2-5a). Impurities, such as particulates, within the dielectric liquid may also result in the formulation of these low-density regions (Figure 2-5b).

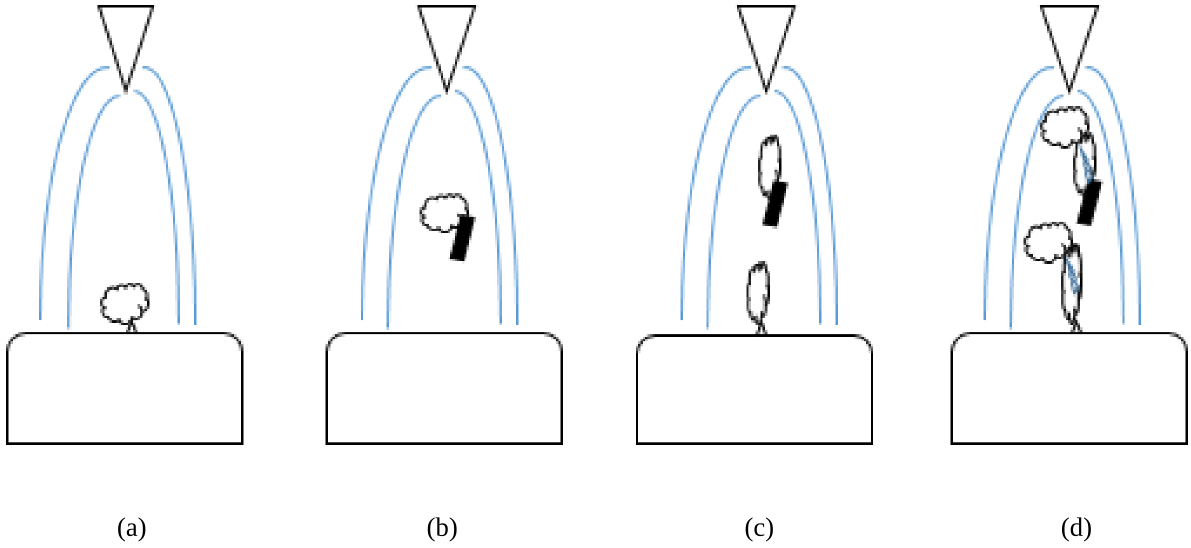


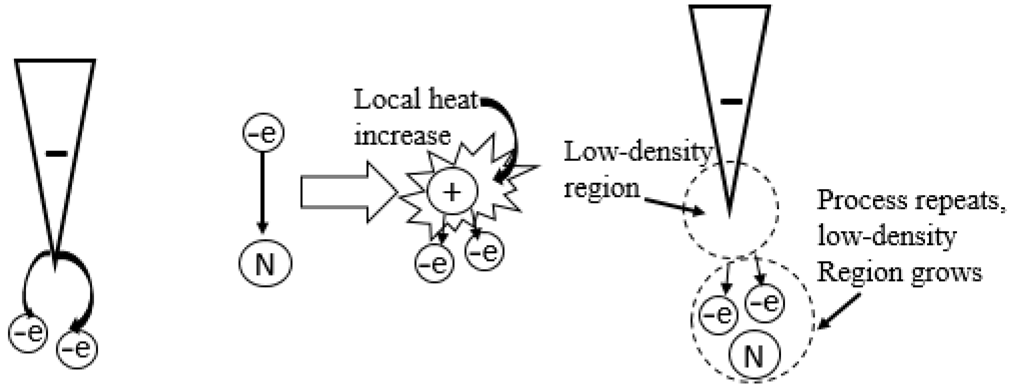
Figure 2-5; *Overview of bubble theory; (a) low-density region appears on cathode; (b) low-density region appears on a particle present within the fluid; (c) low-density regions grow; (d) breakdown occurs within the low-density regions. In the figure rectangles represent particles such as metal, dust or cellulose fragments on which the low-density region (represented by the cloud symbol) appears.*

In [55] Krasucki observed the inception of bubbles originating from particulates within the volume of the liquid which grow continually after their appearance, providing they were of sufficient size and the field stress is maintained. This growth was also reported by Kao in [56], [57] where it was determined that once created, a bubble will be stretched along the electric field lines (Figure 2-5c) until this elongation reaches a critical value were the internal pressure corresponds with the minimum value on the Paschen curve for the occurrence of partial discharge at which time breakdown of the cavity will take place. This internal breakdown within the volume of the bubble will result in distortion of the electric field and cause an enhancement of the field at the extremity of the cavity. This increased field intensity will result in the formulation of another low-density region just ahead of the previous [58] (Figure 2-5d). This process will repeat continually until the complete inter-electrode gap is bridged, providing the field stress is maintained.

2.3.3. Ionisation of liquid in strong electric field

This breakdown theory has been extensively studied since the 1940s in an attempt to link the observations made in the study of gas breakdown to that of dielectric liquids. During these early studies into ionisation of liquids in which high electric field stress (>1MV/cm) was applied to the liquid it was reported that collision based ionisation was not the main mechanism responsible for experimental observations and further investigation was required [59]. This came in the years that followed were Félici went on to experimentally demonstrate that the most likely mechanism responsible for the early ionisation observations was Onsager type field enhanced disassociation [60]. Expansion of this initial theory came with the development of microscopic photographic techniques. In [61], [62] it was shown that when a liquid is exposed to divergent electric fields small low-density regions form near the tip of the high voltage electrode as a result of the high local field magnitude; similar to the mechanism discussed in Section 2.3.2. However, in the case of ionisation bubbles growth is as a result of impact ionisation within the internal gas structure of the bubble resulting in the stretching of the gas channel with the process continuing until complete breakdown of the gap is achieved [63]. Lewis in [64] took these observations further still proposing that ionisation processes differ with the specific energisation polarity.

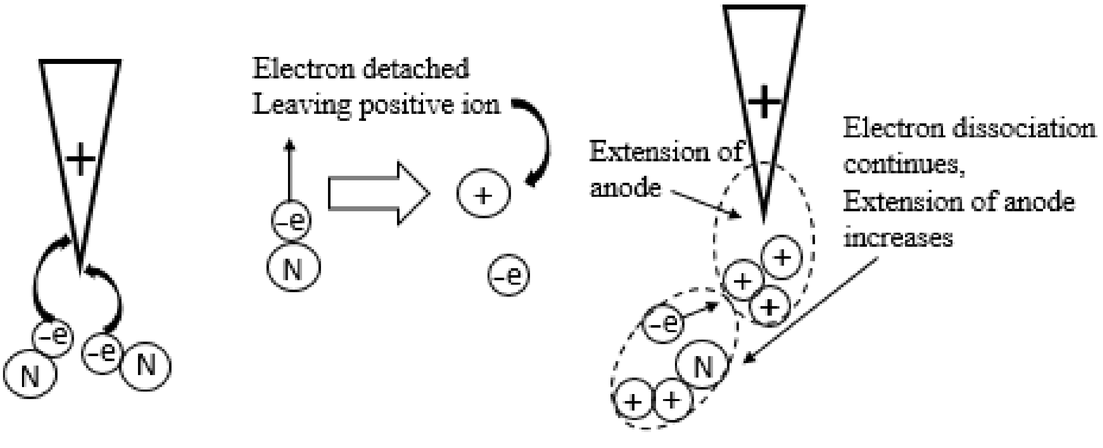
In the case of negative energisation, also known as cathode initiated, electrons will be supplied, or injected, into the liquid volume from the electrode surface. These injected charges, accelerated by the extremely high electric field in the vicinity of the cathode tip, then impact with neutral molecules present within the fluid and ionise them increasing the temperature of the liquid surrounding the molecule resulting in evaporation and creation of another low-density region. The collision between electron and neutral molecule will cause the release of two other electrons from the molecule producing an ion with net positive charge. This positive ion will then drift towards the cathode while the released electrons easily move through the low-density region created by the impact, gaining sufficient velocity to cause further impact ionisation. This process repeats and the low-density region continues to grow until the inter-electrode gap is breached or the external electric field magnitude becomes insufficient to sustain the growth. An overview of the described ionisation process has been given in Figure 2-6.



(a) (b) (c)

Figure 2-6; *Negative polarity ionisation process; (a) electrons are injected from the cathode into the bulk of the liquid; (b) injected electrons collide with neutral molecules; (c) creation and growth of a low-density region.*

The process which occurs under positive energisation, anode initiated ionisation, is completely different to that of negative energisation. Lewis [64] proposed that when ionisation originates from the anode the mechanism of breakdown relies on a process of pseudo-extension of the anode rather than the growth and breakdown of low-density regions within the liquid. This hypothesis was corroborated in further studies [65]-[69] which investigated anode initiated breakdown providing a much more comprehensive explanation of the mechanism.



(a) (b) (c)

Figure 2-7; *Positive ionisation process; (a) electrons are attracted towards the anode; (b) electrons are detached from neutral molecule; (c) pseudo-extension of the anode tip*

When ionisation is initiated from the anode electrons in a free state within the liquid, or more commonly those attached to neutral molecules, are attracted to the anode. This dissociation of electrons results in the creation of ions with positive net change. Due to the large disparity in mobility between these two particles, with electron mobility many orders of magnitude greater than that of an ion, the positive ions remain suspended in the liquid and group together and begin acting as the tip of the anode; attracting more electrons and causing the process to repeat. This can be thought of as a pseudo-extension of the anode tip, illustrated in Figure 2-7.

2.3.4. Plasma streamers: transient ionisation fronts in liquids

Under short duration impulse voltage stress the development of streamers, narrow plasma channels propagating through the liquid the head(s) of which are described as ionisation fronts, have been shown to be the predominate breakdown mechanism in dielectric liquids [13], [14], [69], [70]. The voltages at which these plasma channels appear (initiate) and propagate were defined in [71] by Rzad et al. In their work, the authors clearly define three voltages linked to plasma streamers. The first of these is the initiation voltage (V_i) that corresponds to the voltage at which the streamer appears in the liquid. The second voltage (V_b) the breakdown voltage is the peak voltage amplitude of the energising impulse, which may or may not be the voltage at which breakdown of the liquid occurs. The final voltage discussed by Rzad et al. (V_m) occurs on the tail of the impulse and is the minimum voltage at which the streamer can propagate in the liquid and thus represents the lowest possible voltage at which breakdown of the fluid may occur. While only the breakdown voltage (defined in this thesis as the voltage at which breakdown of the fluid occurs and not the peak amplitude of the impulse) is referred to throughout the experimental work detailed within this thesis it is important to provide a comprehensive explanation of this breakdown phenomenon. Thus, the following sections will be dedicated to the presentation of streamer characteristics as well as their initiation and propagation through dielectric liquids.

2.3.4.1. Plasma streamer characteristics

The morphology, or shape, of individual streamers is heavily influenced by energisation polarity and the specific type of dielectric liquid they propagate within. In [69] Devins et al. study streamer characteristics in mineral oil stressed with 1µs rise-time chopped voltage impulses of both positive and negative polarity using a point-plane electrode geometry. The authors discovered that when under positive energisation developed streamers were of thin filamentary morphology and contained many 'branches', while those developed under negative polarity voltages were less filamentary adopting a more bush-like shape [69]. Similar results were reported within [70] where Sitorus et al. investigated streamer development in both mineral oil and natural ester fluid under standard lightning impulse stress (1.2/50µs). Their work [70] demonstrated that for a comparable level of excitation voltage, positive streamers are much longer and consist of many thin filaments while those developed under negative energisation are more stout and luminous due to their bush-like structure. They also reported no discernible difference in the characteristics of positive streamers developed in the investigated mineral oil and ester fluid. However, streamers developed under negative energisation were seen to grow more rapidly and consist of a greater number of filaments when propagating in ester fluid than when in mineral oil.

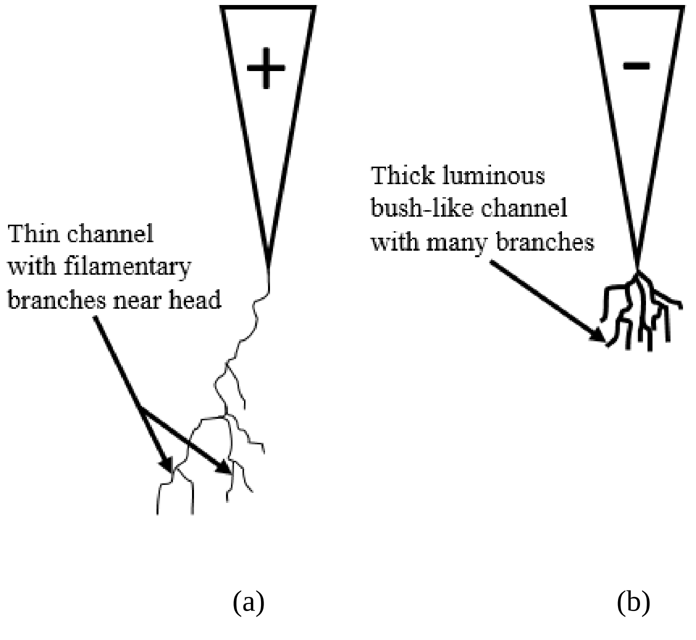


Figure 2-8; *Streamer morphology for (a) Positive and (b) negative streamers*

Streamer development in natural ester fluid was also investigated by Tran Duy et al. in [13] where a number of steel points, ranging from 1µm to 100µm, were used in a point-plane electrode configuration to study streamer inception under standard lightning impulse and switching impulse (250/2500µs) stress. In this work, Tran Duy et al. chose to vary the inter-electrode gap distance from 2cm to 20cm. Much like the work of Sitorus et al. [70], Tran Duy et al. also report that positive streamers are thinner than negative streamers for a given energisation voltage and are of a more filamentary morphology.

The characteristics of streamers developed in synthetic ester fluid have also been examined experimentally. In [14] Viet-Hung Dang, Beroual and Perrier investigate streamers in different unnamed dielectric fluids which include three mineral oils, three natural esters and one synthetic ester fluid. The liquids in their work were stressed with standard lightning impulse voltage and in similar divergent field conditions (point-plane geometry) to those previously discussed [13], [69], [70]. In their work [14] the authors show that for both positive and negative energisation streamers developed in the synthetic ester fluid are longer and more filamentary than those in mineral oil and natural ester for a given level of voltage stress.

2.3.4.2. Initiation of streamer discharge in liquids

Much like the structure of a streamer the level of voltage, or magnitude of electric field, at which it appears is governed by the specific energisation polarity. This is apparent in work conducted by Hestard et al. [72] in which the level of electric field required for the inception of both positive and negative streamers is investigated. During this work the authors stress three different dielectric liquids, a hydrocarbon liquid (Cyclohexane), a mineral oil (Nytro 10X) and a synthetic ester fluid (MIDEL 7131), with high voltage impulses of very short duration (30ns to 50ns rise-time). To ensure adequate streamer inception a point-plane electrode configuration is again used, though unlike the work conducted in [14], the authors of [72] took the decision to use varying tip radii (2µm and 25µm). For all investigated dielectric liquids the authors reported a higher inception field for positive streamers as compared with negative streamers (Figure 2-9). However, the difference in inception field magnitude is minimal, never increasing above 9%; as is the case for both the hydrocarbon liquid and mineral oil. The variation in positive and negative streamer inception field is even lower for the MIDEL 7131 synthetic ester with positive and negative inception field values observed to be within 5% of each other.

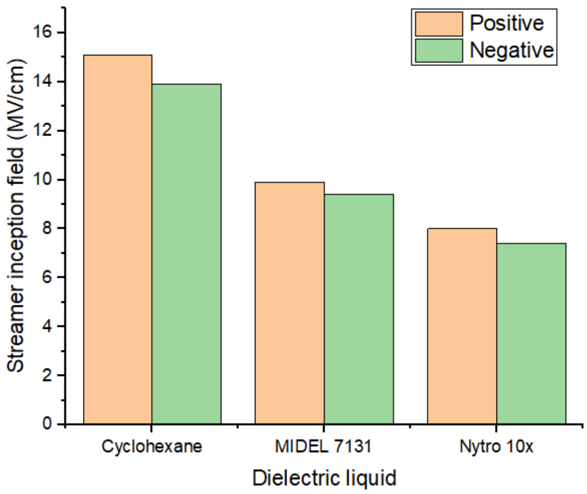


Figure 2-9; *Streamer inception field when stressed with 30ns impulse voltage for hydrocarbon Cyclohexane, synthetic ester MIDEL 7131 and mineral oil Nytro 10X under both positive and negative energisation polarity. Experimental data taken from [72]*

The field magnitude for streamer inception in natural and synthetic ester fluids as well as conventional mineral oil was also investigated by Rozga and Stanek in [73]. The authors tested the aforementioned dielectric fluids under lightning impulse voltages of both positive and negative polarity, again in a point-plane electrode configuration (tip radius = 250µm, gap spacing of 15mm and 20mm). They observed almost no difference in the streamer inception field when energisation polarity was change from positive to negative (Figure 2-10).

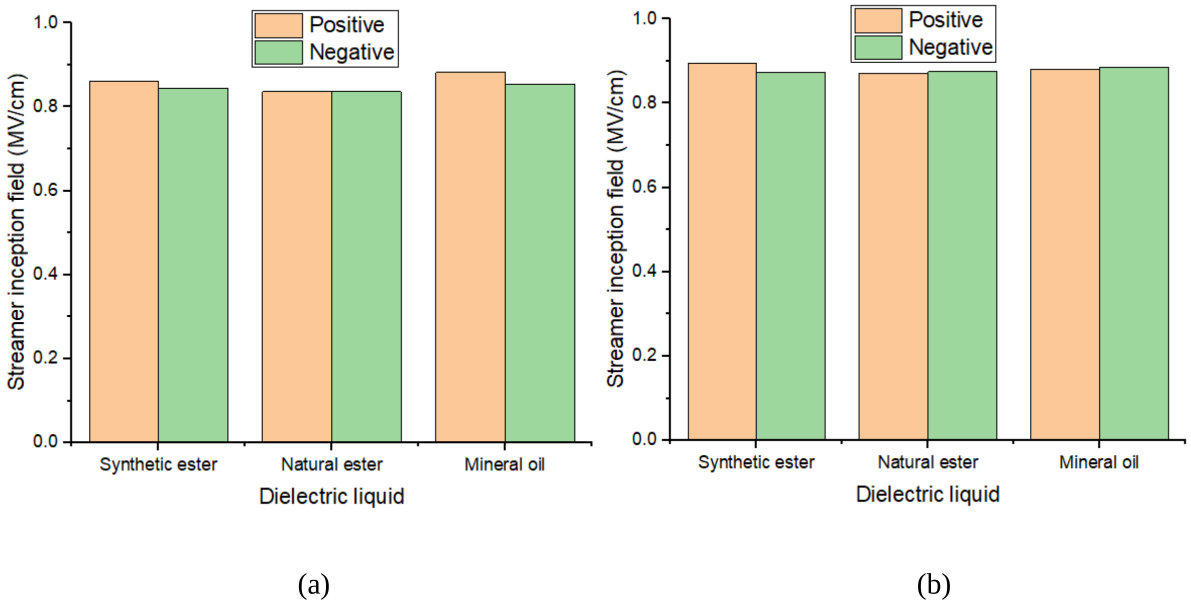


Figure 2-10; *Streamer inception field when stressed with 1.2µs impulse voltage for synthetic ester, natural ester and mineral oil when inter-electrode gap was (a) 15mm and (b) 20mm. Experimental data taken from [73]*

As can be seen when comparing Figures 2-9 and 2-10, the magnitude of field required for the inception of a streamer within dielectric liquid is heavily influenced by the impulse rise-time parameter, as well as the nominal radius of the high voltage electrode; with the field necessary for streamer inception significantly higher in the work conducted by Hestard et al. [72] where rise-time of the impulse is significantly shorter, and tip radius considerably sharper, than that used by Rozga and Stanek [73] (rise-time 30ns, tip radius ~2µm as compared with 1200ns and 250µm).

2.3.4.3. Streamer propagation

The velocity at which a streamer propagates in a dielectric liquid can be broadly categorised as ‘slow’ (those with a velocity of 1-2km/s) and ‘fast’ (those with velocity of tens or hundreds of km/s). This method of differentiating streamers as ‘fast’ and ‘slow’ based on propagation velocity was further developed by Lesaint [74] and Hebner [75]. The latter in [75] proposed a classification system where streamers could be grouped into ‘modes’ based on their average propagation velocity. ‘Slow’ streamers which propagate at only a few km/s were designated as mode “1” or “2”. Those previously termed as ‘fast’ were also subdivided into two modes; mode “3” for those travelling at speeds of tens of km/s and mode 4 for those with velocities of hundreds of km/s. Lu and Liu investigated this further and discovered that streamers can accelerate or decelerate as they propagate through the dielectric liquid, observing combinational streamer modes such as “2+3” or “3+4” [76]. In [76] the authors studied streamer initiation and propagation in mineral oil (Shell Diala S3 and Shell Diala S4) under positive lightning impulse voltage and reported that as a streamer moves through the volume of the liquid its velocity will vary; increasing if the applied voltage is above the acceleration voltage threshold (220kV for Shell Diala S4 for a 50mm inter-electrode gap) and decreasing if voltage is below this threshold value. Streamer propagation in naphthenic mineral oil has been shown to be dependent on the concentration of specific compounds within the fluid. In [13] Devins et al. conclude that non-ionic compounds have a significant influence on the propagation of positive streamers; with a velocity increase of 100-200% observed when these compounds are present in a liquid. However, the authors observed no such effect in the propagation velocity of streamers developed under negative energisation. There was however a similar acceleration effect observed for negative streamers developed in a high-purity hydrocarbon liquid (cyclohexane) by Beroual et al. in [61] when electron scavenging compounds were added to the fluid. This effect was also observed when the same compounds were added to naphthenic mineral oil; where again negative streamer velocity was increased but positive streamer velocities were unaffected.

The propagation velocity of streamers in ester fluid has been shown to be higher for a given level of voltage, or electric field, than those in mineral oil; attributed the inability of ester fluids to prevent streamers transitioning to the fastest '4th mode'. In [77] Duy et al. experimentally demonstrate that both positive and negative streamers propagating in ester liquid quickly transition from the slower 2nd mode to the much faster 4th mode when under impulsive voltage stress. The authors attribute this characteristic of ester fluids to an absence of polyaromatic compounds which have been shown to inhibit the development of the faster 3rd and 4th mode streamers in tests conducted with mineral oil. This resistance to 3rd and 4th mode streamers associated with the presence of polyaromatics is postulated by the authors of [78] to be as a consequence of a dampening of the electric field acting on the streamer near the head due to an increase in streamer filaments and thus surrounding space charge.

As is clear from the work conducted in [77] and [78], the chemical composition of a dielectric fluid plays a crucial role in streamer development and propagation. An extensive study of streamers in dielectric fluids was conducted by Beroual et al [79] in which the authors investigated the inception and propagation of streamers in more than thirty different dielectric fluids under a number of positive and negative voltage impulses with rise-times varying from several nanoseconds (15ns) to those of many microseconds (4µs). The authors concluded that the molecular structure of the fluid has a significant effect on streamer propagation, which they attribute directly to differences in electron affinity. In their work [79] it is shown that the presence of a single halogen atom, such as chlorine, can result in a velocity increase in negative streamers of almost one order of magnitude. Positive streamers are also influenced by the presence of such halogen atoms with an increase in the amount of filaments observed; though propagation velocity is unaffected.

Further to the chemical composition, there are a number of other varying factors which may affect the development and propagation of streamers within a particular dielectric liquid. The mode at which a streamer propagates has also been shown in [80] to depend upon the magnitude of electric field applied to the liquid and therefore is linked to parameters of the energised electrode. In [80] an investigation was conducted into the initiation and propagation of streamers in high purity hydrocarbons as well as liquefied gases, fluorinated fluids and transformer oils (mineral oil). The authors of [80] determined that the tip radius of the energised electrode has a significant effect on the magnitude of external electric field required for streamer inception. In the case of the smallest tip radii (<3µm) the field necessary for streamer inception was approximately one order of magnitude higher than that of the largest tip radii (>100µm). Electrode tip radius was also shown in [80] to have an effect on the structure of negative streamers developed in cyclohexane with smaller tip radii (~0.5µm) shown to develop more spherical streamers, while more bush-like streamers developed by larger radii (~15µm). The influence of hydrostatic pressure was also investigated in [81] where it was concluded that only an increase in pressure has any evident effect on streamer development. As hydrostatic pressure is raised to above that of atmospheric an immediate reduction in streamer length and filaments was observed. Once this pressure reaches a threshold level, dependant on streamer energy, the streamer is quenched and the streamer, all associated current pulses and emitted light vanishes.

The voltage at which streamers in ester fluids and mineral oil transition from the slower first and second mode to the much faster third and fourth mode, known as the acceleration voltage, was studied in [15]. The authors of [15] investigate streamer propagation in Envirotemp FR3 natural ester, MIDEL 7131 synthetic ester and Gemini X mineral oil under divergent electric field conditions using a needle-plane configuration (tip radius = 50µm, gap spacing of 50mm) when applying both positive and negative lightning impulse voltages.

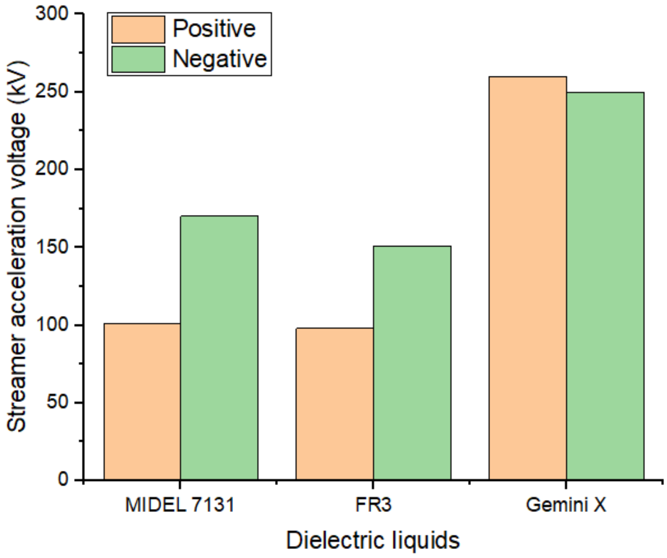
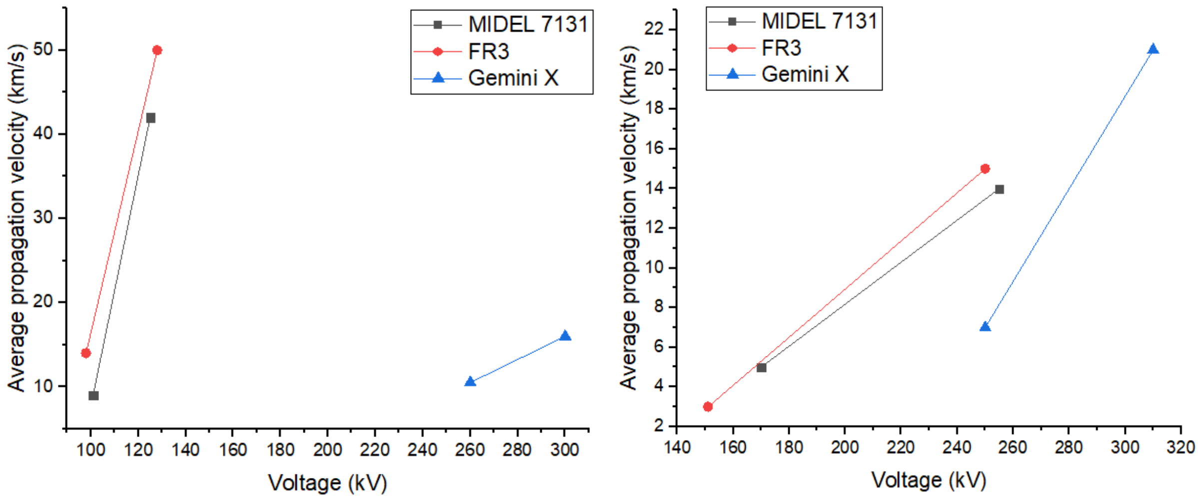


Figure 2-11; *Streamer acceleration voltage for synthetic ester MIDEL 7131, natural ester Envirotemp FR3 and mineral oil Gemini X stressed with positive and negative 1.2µs impulses. Data from [15].*

As is evident from the data presented in Figure 2-11 the authors found that in all tested cases the transition from slow to fast streamers occurs at a lower level of voltage for ester liquids than for mineral oil, irrespective of impulse polarity. Both ester fluids exhibit similar levels of acceleration voltage when comparing values for a given impulse polarity, with the natural ester performing only slight worse than the synthetic fluid under both positive and negative impulse; 3% and 12% respectively. It is clear from Figure 2-11 that under the test conditions applied in [15] streamers in mineral oil have a much greater resistance to mode transition than those in ester fluid; requiring a much higher level of voltage for acceleration to occur. In the case of positive impulse stress, the acceleration voltage of mineral oil was approximately 2.5 times higher than that of both ester fluids. When under negative energisation acceleration in mineral oil again required a higher level of voltage than in both the synthetic and natural ester liquids; ~50% and ~65% respectively. Interestingly in the case of mineral oil the voltage necessary for positive streamer acceleration was ~5% higher than that of negative streamers; this may be attributed to the presence of polyaromatics within the fluid. In the case of the ester fluids acceleration voltage for positive streamers was always lower than that of negative.



(a) (b)

Figure 2-12; *Average propagation velocities for (a) positive and (b) negative streamers developed in synthetic ester MIDEL 7131, natural ester Envirotemp FR3 and mineral oil Gemini X when under lightning impulse voltage (1.2/50µs). Experimental data taken from [15]*

When examining the data provided in [15] on average propagation velocities of streamers, summarised as the minimum and maximum average propagation velocities in Figure 2-12, it is evident that for a given level of voltage streamers propagating in ester fluids have a higher velocity than those travelling in mineral oil, irrespective of energisation polarity. Differing propagation behaviour does exist for all investigated liquids when examining data for a given polarity of impulse. When the energising impulse is of positive polarity streamers propagating in the natural ester fluid are seen to move faster than both the synthetic ester and mineral oil. However, it must be said that streamers in both ester fluids are observed to accelerate quickly from ~10-15km/s to ~40-50km/s; with this acceleration occurring over a small increase in energisation voltage (~30kV). Positive streamer velocity in mineral oil remains fairly constant over a similar (~40kV) voltage range only increasing by ~6km/s. When the voltage impulse is negative streamer acceleration again occurs at a lower level of voltage for both ester fluids than for mineral oil. As with positive voltage stress streamers in the natural ester fluid are seen to accelerate at the lowest level of voltage, ~150kV. When under negative stress the increase in streamer velocity (~10km/s) as well as the maximum velocity of propagation is much lower than that of streamers propagating under positive stress for both ester fluids; with negative streamer velocity not exceeding 15km/s for these fluids; as compared with ~40-50km/s for positive streamers. The range of voltage at which this increase in propagation velocity occurs is also much larger than that observed under positive stress; 90kV for the synthetic ester and 120kV for the natural ester, as compared with ~30kV for both fluids under positive energisation. This is not the case for negative streamers propagating in mineral oil where a larger increase in streamer velocity is observed, ~14km/s, over a smaller voltage range ~60kV than that of negative streamers in ester fluid. The maximum velocity at which streamers propagate in mineral oil is also observed to the higher than that of both the natural and synthetic ester fluids when the energising voltage is of negative polarity.

2.4. Impulse breakdown of dielectric fluids

The study of dielectric fluids under impulse voltage stress is of great importance as stressing liquids under such conditions yields information about their intrinsic dielectric properties [16], [82]. To allow for comparability of experimental results between varying research works one of two standardised testing methodologies is normally applied during the impulse breakdown testing of dielectric fluids; IEC60897 [82] or ASTMD3300 [83].

2.4.1. Comparison of AC and impulse breakdown

When exposed to impulse voltages insulating liquids will always exhibit a higher dielectric strength than when tested under AC voltage, providing the experimental conditions (electrode configuration, level of field divergence, fluid condition, moisture content, temperature, liquid pressure, etc.) are identical [84]. In [85] Martin et al. investigate the breakdown of natural and synthetic ester fluids and conventional mineral oil under both AC and lightning impulse voltages; in accordance with ASTM D1816 and ASTM D3300 standards respectively.

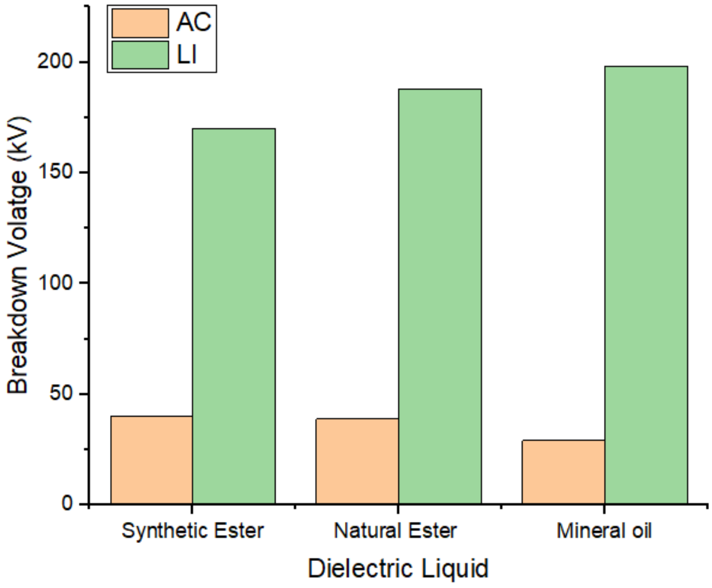


Figure 2-13; *AC (60Hz) and Lightning impulse (1.2/50µs) breakdown voltage, gap distances 1mm and 3.8mm respectively, for synthetic ester, natural ester and mineral oil when fluids are at 10% relative humidity. Experimental data taken from [85].*

From the data extracted from [85] and presented in Figure 2-13 it is clear that lightning impulse breakdown strength of all investigated dielectric fluids is significantly higher than that obtained under AC voltage stress. It must be said however that due to the authors of [85] taking the decision to test the fluids in accordance with standardised testing methods ASTM D1816 and ASTM D3300 the experimental conditions were not identical for both tests, with gap spacing significantly longer in the tests conducted under ASTM D3300. This dissimilarity in testing conditions will have some effect on the absolute level of breakdown voltage obtained for each fluid but the overall trend of lightning impulse breakdown voltage being higher than AC breakdown voltage would remain unchanged.

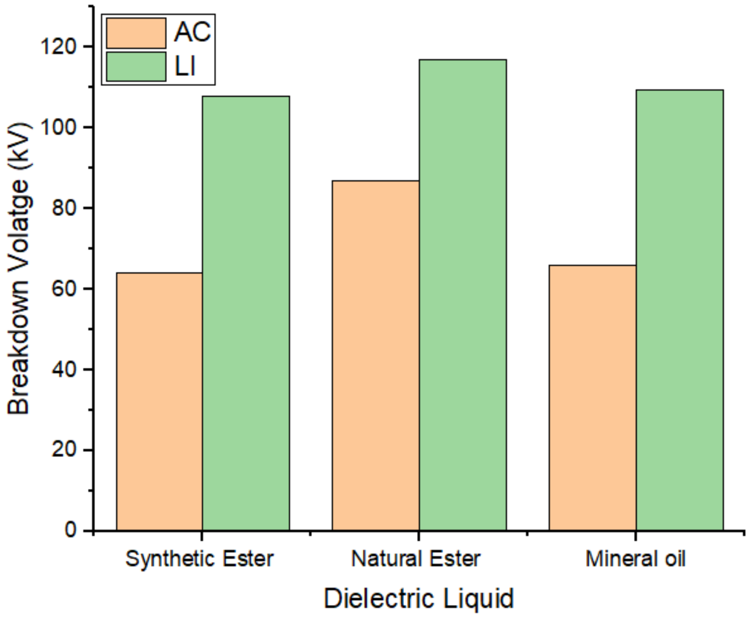
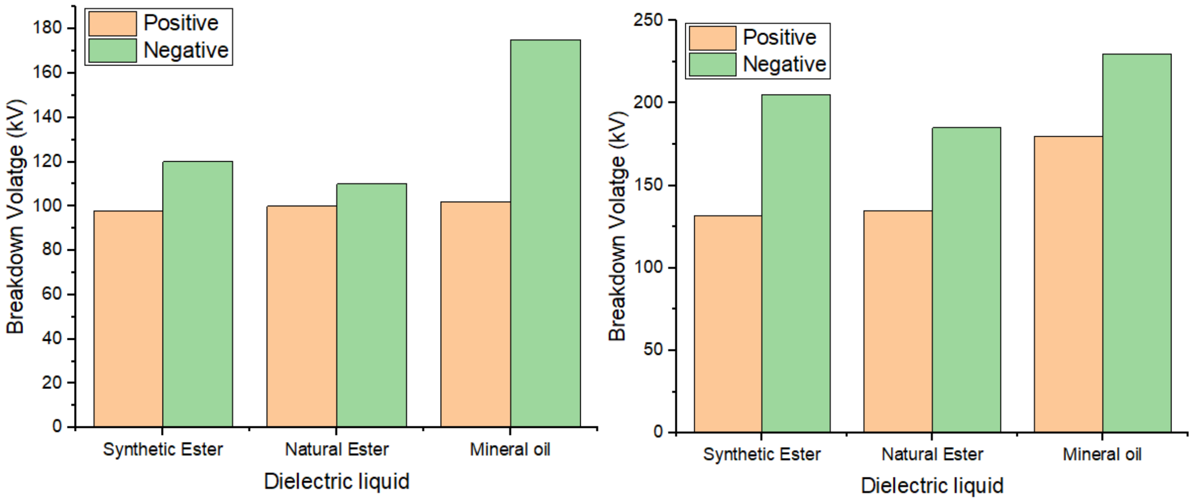


Figure 2-14; *50% probability of breakdown voltage under AC (50Hz) and lightning impulse (1.2/50µs) stress for synthetic ester, natural ester and mineral oil, inter-electrode gap set at 2.5mm. Experimental data taken from [84].*

This is confirmed in work conducted by Reffas et al [84] in which identical testing conditions were maintained for both AC and lightning impulse tests. In their work [84] the authors test natural ester fluid (Rapeseed oil), synthetic ester fluid (tetra-ester) and mineral oil in sphere-sphere electrode configuration (sphere diameter = 12.5mm, gap spacing of 2.5mm) applying either an AC (50Hz) voltage or standard positive polarity lightning impulse voltage to the liquid sample. As is evident from the results summarised in Figure 2-14 which pertain to the 50% probability of breakdown voltage ($V_{50\%}$) of each liquid, the same trend exists as in [85], namely, that lightning impulse breakdown always occurs at a higher level of voltage than AC breakdown. When tested under identical experimental conditions it is evident from Figure 2-14 that the disparity in AC and lightning impulse breakdown voltage is much smaller than it was in the case of the tests conducted in [85].

2.4.2. Effect of impulse polarity

The energisation polarity of the voltage impulse has a significant effect on the dielectric strength of insulating liquids. This is as a result of the influence voltage polarity has on ionisation processes, streamer initiation and propagation and volumetric space charge development. In [86] Nguyen Ngoc et al. investigate the breakdown of natural and synthetic ester fluid as well as a conventional mineral oil stressed with positive and negative impulse voltage, 0.5/1400µs, in a point-plane configuration over two inter-electrode gap distances (5cm and 10cm).

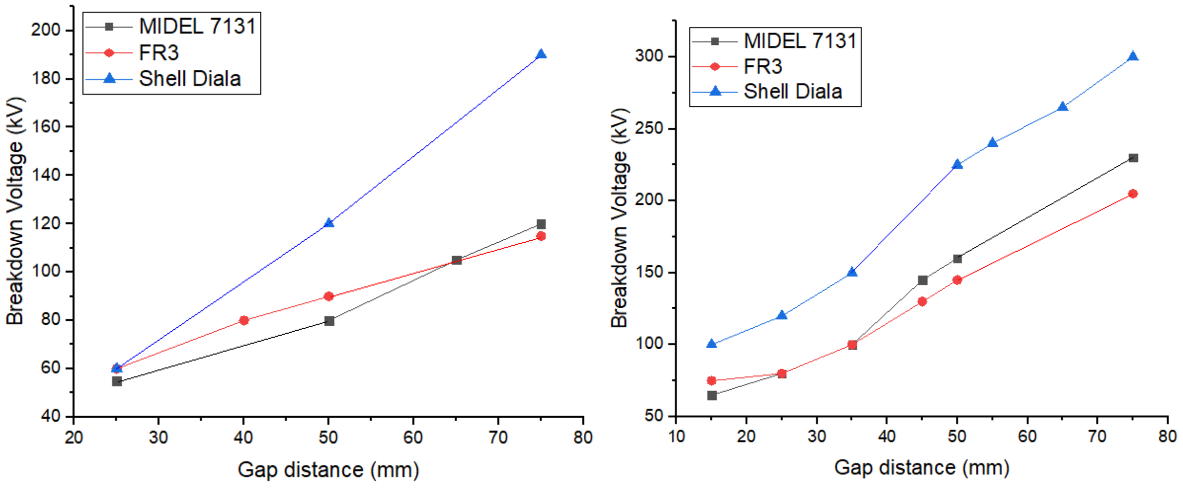


(a) (b)

Figure 2-15; *Positive and negative breakdown voltage for synthetic ester, natural ester and mineral oil measured at inter-electrode gap distances of (a) 5cm and (b) 10cm when stressed with 0.5/1400µs impulse. Experimental data taken from [86].*

In [86] it is shown that irrespective of gap spacing breakdown of the all dielectric fluids occurs at a lower level of voltage when the energisation polarity is positive. There are however differing levels of disparity in positive and negative breakdown voltages for the three dielectric fluids at the two examined inter-electrode gap distances. In the case of the shorter gap (5cm) positive breakdown voltage of the three fluids occurs at a comparable level with only a 4% variation observed between the highest breakdown voltage (mineral oil) and the lowest (synthetic ester). The disparity however is seen to widen when the impulse is of negative polarity, as well as a change in which fluid exhibits the lowest level of breakdown voltage; with natural ester fluid now having the lowest breakdown strength ~59% lower than values recorded for the mineral oil tested. Under both positive and negative impulse both ester fluids can be seen to exhibit comparable levels of breakdown voltage at the shorter gap distance (5cm) with only a ~9% difference observed in the most extreme case (negative polarity impulse). When the gap distance is extended to 10cm the observed trends in breakdown voltage for the mineral oil are seen to invert. The difference in positive and negative breakdown voltage for mineral oil is seen to reduce at the longer gap distance; where now only a ~28% difference in positive and negative breakdown voltage exists as compared with a ~72% difference at the shorter gap distance. This trend opposes that observed for the two ester fluids where differences in positive and negative breakdown voltage are seen to increase when the gap distance is increased. Again both ester fluids are seen to offer similar dielectric performance at the longer gap distance with disparity in breakdown voltages between the fluids only ~3% for positive polarity breakdown and ~11% for negative polarity breakdown.

Similar results to those of Nguyen Ngoc et al. [86] were reported by Liu and Wang in [15], where the authors tested synthetic ester MIDEL 7131, natural ester Envirotemp FR3 and mineral oil Gemini X under positive and negative impulse stress in a point-plane configuration (tip radius = 50µm) across a number of inter-electrode gap distances (15mm to 100mm); although only results up to a gap distance of 75mm were reported for breakdown under negative polarity impulse.



(a) (b)

Figure 2-16; *50% probability of breakdown voltage under (a) positive and (b) negative energisation for synthetic ester MIDEL 7131, natural ester Envirotemp FR3 and mineral oil Shell Diala at gap distances of 15mm to 75mm. Experimental data taken from [15].*

The $V_{50\%}$ breakdown voltages reported in [15] have been summarised in Figure 2-16. As with the results for positive polarity breakdown in [86], the disparity in breakdown voltage recorded for the ester fluids and mineral oil is at a minimum for the shortest examined gap distance and grows with the increase in inter-electrode gap distance. The ester fluids again demonstrate similar dielectric strength across all gap distances. Interestingly though there is a crossover point observed (at 65mm for positive breakdown and 35mm for negative) after which the synthetic ester fluid always exhibits higher breakdown strength than the natural ester fluid; whereas before this point breakdown strength of the synthetic fluid was either the same or lower than that of the natural ester. Breakdown voltage of the mineral oil, irrespective of impulse polarity, is always seen to be higher than that of the ester fluids, with the largest disparities again observed under positive voltage stress and at the largest gap distances.

Dual polarity lightning impulse breakdown of synthetic ester fluid and conventional mineral oil was also investigated by Rozga, Stanek and Rapp in [87]. During this work the authors applied standard lightning impulse voltages to samples of MIDEL 7131 synthetic ester, Envirotemp 200 synthetic ester and Shell Diala mineral oil. An IEC60897 point-sphere electrode configuration was used in this work (tip radius = 50μm, sphere diameter 13mm) with the inter-electrode gap set at 25mm.

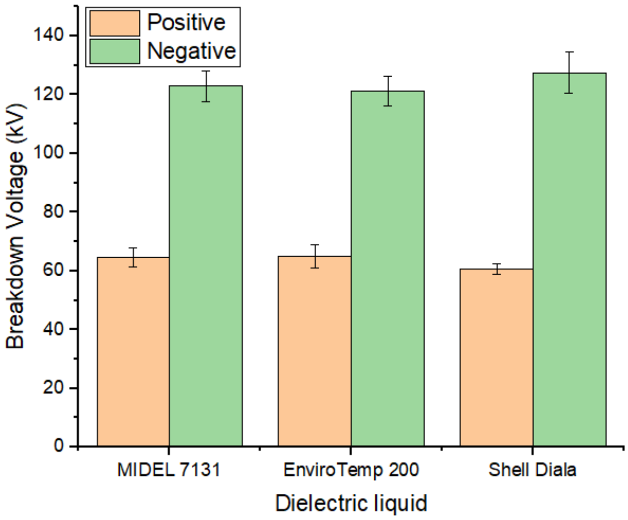


Figure 2-17; *Positive and negative breakdown voltage of synthetic ester fluids MIDEL 7131, Envirotemp 200 and mineral oil Shell Diala under lightning impulse stress (1.2/50μs). Experimental data taken from [87].*

In the work conducted in [87] the authors state that breakdown consistently occurred on the falling slope of the waveform as opposed to the rising edge; this is clearly apparent when examining the time to breakdown data provided in [87]. Due to this falling slope breakdown it is not clear what the absolute dielectric strength of each of the examined fluids is, as peak voltage magnitude is not provided by the authors. Similarities in the breakdown voltages provided in [87], summarised in Figure 2-17 can also be attributed to this falling edge breakdown and thus little information pertaining to the true dielectric capabilities of the fluids can be extracted from this data; highlighting the importance of the inclusion of time to breakdown data and that of peak voltage amplitude experienced by the samples during testing.

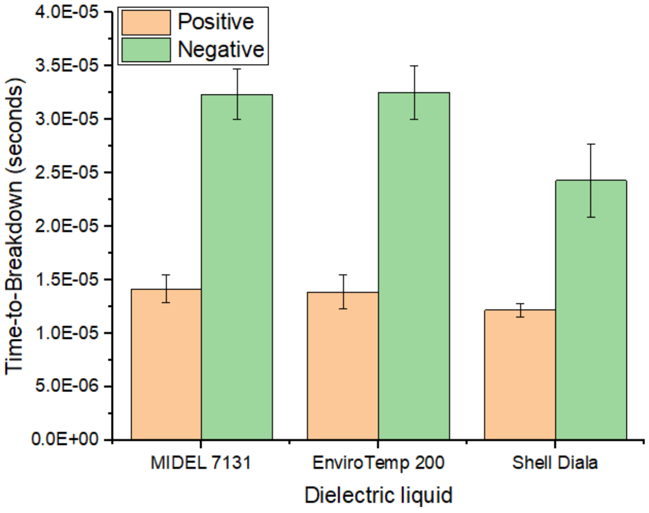


Figure 2-18; *Positive and negative time to breakdown of synthetic ester fluids MIDEL 7131, Envirotemp 200 and mineral oil Shell Diala under lightning impulse stress (1.2/50µs). Experimental data taken from [87].*

When the time to breakdown data provided in [87] is examined, it is clear that for both impulse polarities the synthetic ester fluids offer better dielectric performance as they are able to withstand the voltage stress for longer than the tested mineral oil. This is not immediately clear when evaluating the breakdown voltage data only and reaffirms the importance of the provision of time to breakdown data in impulse breakdown testing of dielectric liquids.

2.4.3. Effect of field non-uniformity

It is reported that the difference in the impulsive breakdown performance of dielectric liquids depends on the inter-electrode distance and the field utilisation factor, η. This factor, which is also known as the Schwaiger Factor, provides a measure of field non-uniformity in the inter-electrode gap: η is the ratio of the average field in the gap to the maximum field at the point electrode; derived from equation 2-1:

$$\eta = \frac{E_{av}}{E_{max}} \tag{2-1}$$

where E_{av} is the average field in the centre of the inter-electrode gap and E_{max} is the maximum field generated at the high voltage point electrode; calculated from equations 2-2 and 2-3 respectively.

$$E_{av} = \frac{V}{d} \qquad (2\text{-}2)$$

where V is the magnitude of the applied voltage, expressed in volts and d is the inter-electrode gap distance expressed in meters.

$$E_{Max} = \frac{2V}{r\ln\left(\frac{4d}{r}\right)} \qquad (2\text{-}3)$$

where V is the applied voltage magnitude (in volts), r is the radius of the point electrode expressed in meters and d is again the inter-electrode gap distance expressed in meters.

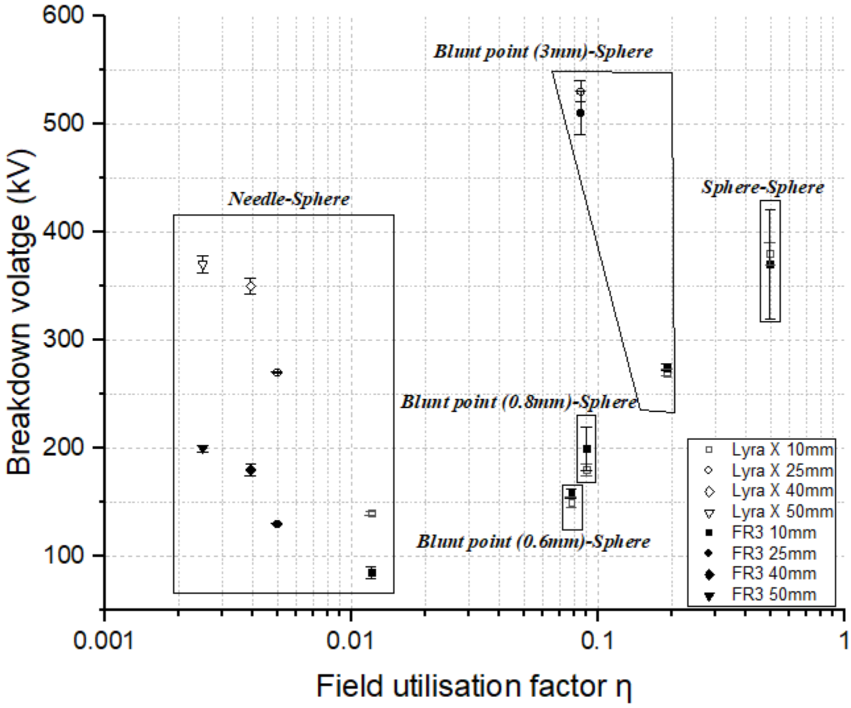


Figure 2-19; *Effect of field non-uniformity on the breakdown voltage of natural ester Envirotemp FR3 and mineral oil Nytro Lyra X under negative lightning impulse stress. Experimental data taken from [88].*

In [88] breakdown voltages of Envirotemp FR3 natural ester and Nytro Lyra X mineral oil are reported as a function of η. The breakdown tests described in [88] were conducted in accordance with the ASTM D3300 standard using negative lightning impulses. In the work [88] the authors use a number of different electrode configurations including needle-sphere, blunt point-sphere and sphere-sphere which allow for a wide range of field utilisation factors to be studied. The reported data for each of the investigated dielectric liquids over the range of inter-electrode gap distances used in the study (10-50mm) has been summarised in Figure 2-19. It was shown that for η in the range of ~0.08 – 0.4, there is similarity in the breakdown voltages of Envirotemp FR3 natural ester and Nytro Lyra X mineral oil. However, for η ~0.04 - 0.07 and below the breakdown voltage of the ester liquid is significantly lower than that of the mineral oil, for example for η ~0.02 this difference in the breakdown voltages is ~43%.

2.4.4. The effect of impulse rise-time

When dielectric liquids are exposed to impulse voltages the rise-time, or wave-front time, of the impulse has been shown to exert an influence over the dielectric strength of the fluid. This phenomenon is not extensively studied by researchers as most impulse breakdown studies involving dielectric liquids are conducted under the methodologies outlined in IEC60897 [82] and ASTM D3300 [83] standards. This is not of much concern to operators of power system assets, such as transformers, as typically the electrical stresses experienced by these machines are well represented within tests conducted under the aforementioned standards. This however is not the case when it comes to pulsed power machines which are routinely stressed with voltage impulses both shorter and longer than the standard lightning impulse used in IEC60897 and ASTM D3300 tests [47]. Thus in order for pulsed power operators to have the confidence to use a particular insulating liquid its dielectric performance must be evaluated under non-standard voltage stress.

One such study evaluating the dielectric performance of insulating fluid under non-standard voltage impulses is [89]. In [89] Ni et al. report results from impulse breakdown tests performed on an unnamed mineral-based transformer oil. The study involved energising a rod-plane electrode configuration (tip radius = 250µm, gap spacing of 4mm) with five discrete positive voltage impulses of rise-times ranging from 0.13µs to 6µs. The authors report the 50% probability of breakdown voltage ($V_{50\%}$) extracted from Weibull plots, this data has been summarised in Figure 2-20.

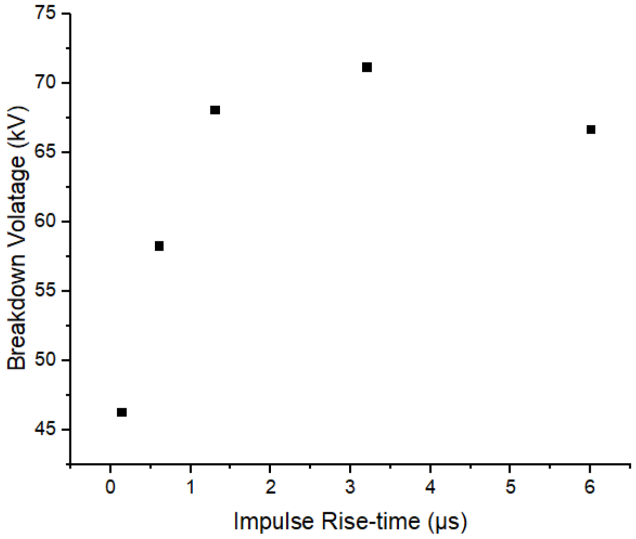


Figure 2-20; *The effect of impulse rise-time on the positive polarity impulse 50% probability of breakdown voltage of transformer oil. Experimental data taken from [89].*

From Figure 2-20 it is obvious that the rise-time of the voltage impulse does influence the dielectric strength of transformer oil under positive impulse stress. An increase in breakdown strength is observed by the authors of [89] until the impulse rise-time exceeds 3.2μs; attributed by the authors to streamer initiation requiring a higher field magnitude when the impulse is longer. It is reasonable to assume that this observation is a consequence of additional space charge accumulation within the inter-electrode gap dampening the applied field and thus reducing its magnitude. At the longest voltage impulse (6μs) breakdown voltage is seen to reduce; it can be concluded that this reduction is a consequence of a change in the mechanism dominating the breakdown process from one of ionisation to one of electrostriction (bubble formation).

In [90] the volt-time characteristics of transformer oil are evaluated under negative impulse stress. The study involved a naphthenic mineral oil tested in a point-sphere electrode configuration (tip radius = 40-70μm, sphere diameter = 12.7mm and gap spacing of 10mm). The volt-time characteristics established during the experimental work have been provided in Figure 2-21.

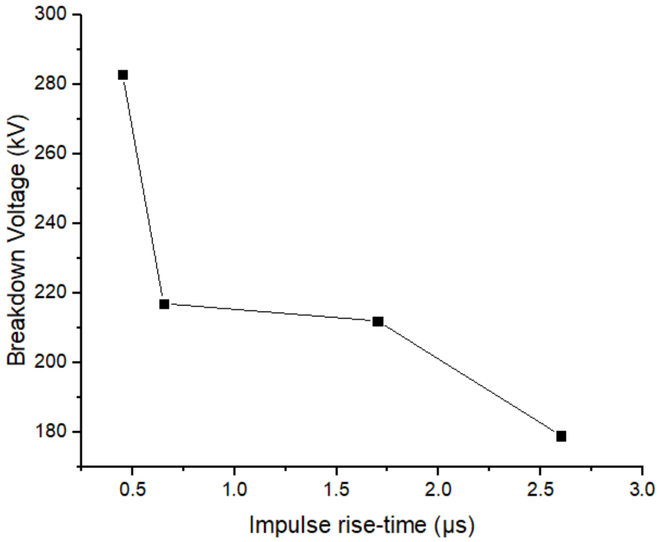


Figure 2-21; *The effect of impulse rise-time on the negative polarity impulse breakdown voltage of transformer oil. Experimental data taken from [90].*

Unlike the tendencies reported in [89], the results published in [90] show a clear downward trend in breakdown voltage as the rise-time of the impulse is increased. This, as stated by the authors of [90], is in accordance with the "general dielectric pattern" and is much more typical behaviour for dielectric liquids.

Similar behaviour to that presented in [90] was observed in work conducted by Timoshkin et al. in [91]. Their work investigated the volt-time characteristics of synthetic ester fluid (MIDEL 7131) and conventional mineral oil (THESO). The authors tested the dielectric fluids under impulse voltage in a needle-plane configuration with an inter-electrode gap of 1mm.

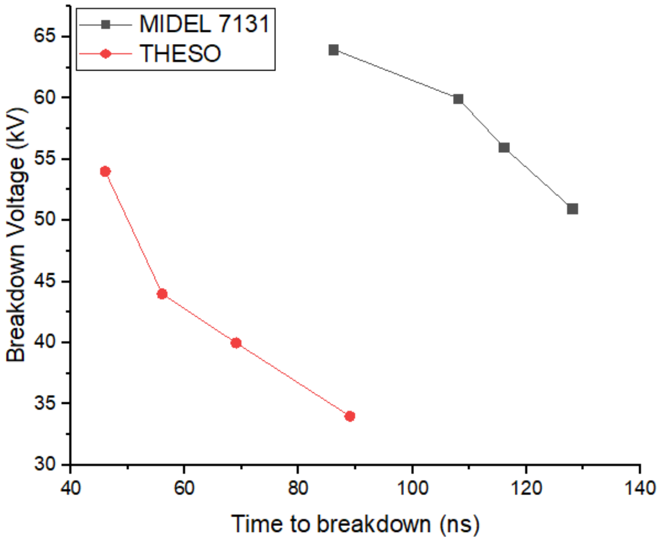


Figure 2-22; *The effect of impulse rise-time on the impulse breakdown voltage of synthetic ester MIDEL 7131 and mineral oil THESO. Experimental data taken from [91].*

Their results, summarised in Figure 2-22, show a similar downward trend in breakdown voltage of the insulating fluids to that reported by Mazzetti and Pompili in [90]. Under the testing conditions used by Timoshkin et al. the synthetic ester clearly demonstrates more desirable volt-time characteristics than the investigated mineral oil; with breakdown voltage consistently higher and exhibiting less of a decrease as the rise-time of the impulse is increased (~20% as compared with ~37% for the mineral oil tested).

2.5. The effect of moisture on the breakdown characteristics of insulating fluids

How the absolute water content, also known as the relative humidity, of a dielectric fluid effects its dielectric performance has been extensively reported in literature [91]-[93]. Experimental work done to quantify the effect of water content on dielectric strength is typically conducted under AC voltage stress as this form of breakdown testing is much more sensitive to the presence of water and other contaminants within the dielectric liquid than impulsive breakdown tests [9], [10]. Under AC voltage stress the presence of water in dielectric liquids is almost universally reported to result in a reduction in the dielectric strength of the liquid.

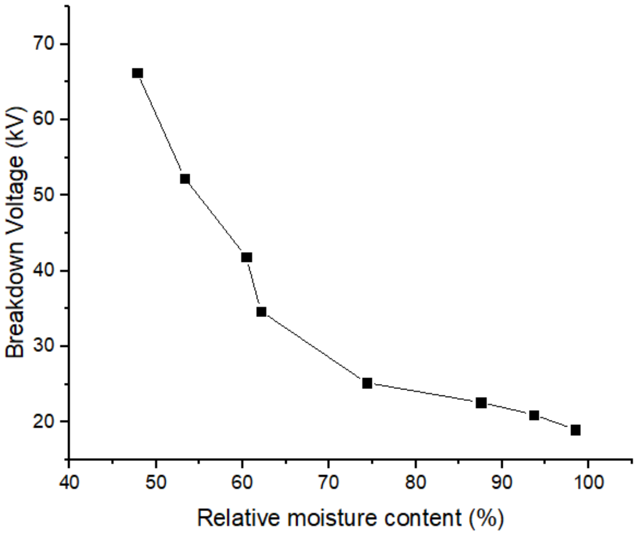
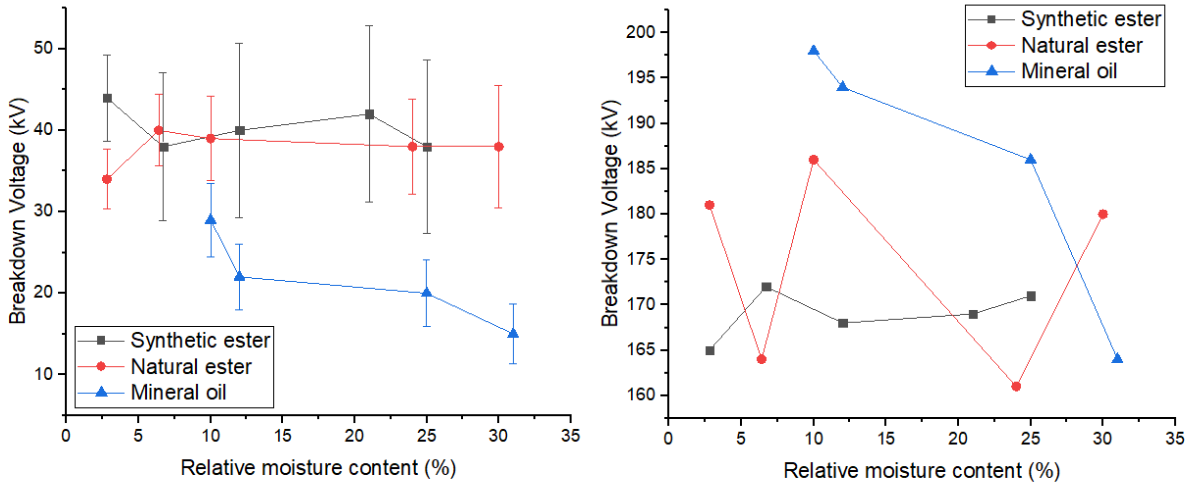


Figure 2-23; *The effect of relative humidity on the AC breakdown voltage of Shell Diala AX mineral oil. Experimental data taken from [92].*

In [92] the effect of relative humidity on the breakdown strength of Shell Diala AX was evaluated, with results from the study summarised in Figure 2-23. Testing of the transformer oil involved stressing the liquid samples of varying moisture content with AC voltage using brass VDE electrodes in accordance with the ASTM D1816 standard testing procedure [94]. As is evident from Figure 2-23 there is a clear degradation in breakdown strength of the fluid as the relative moisture content is increased. A reduction of ~21% occurs immediately after the relative humidity is increased past the base level with this drop in breakdown voltage reaching almost 70% as the water content of the fluid reaches close to the saturation limit.

The effect of relative humidity on the breakdown strength of transformer oil, as well as synthetic ester fluid, was also reported in [93]. Breakdown of the fluid samples was conducted under IEC60156 [95] testing standards. The authors of [93] observed a ~60% drop in breakdown voltage of the transformer oil at ~40% relative humidity while the synthetic ester fluid experienced a much lower ~45% drop in breakdown strength at the same level of relative humidity. Furthermore, as ester fluid can accommodate greater levels of moisture the absolute water content at which these reductions were observed was significantly higher for the ester fluid; 440ppm as compared with 28ppm for the transformer oil.

In [96] Martin et al. investigate the dielectric performance of mineral oil as well as natural and synthetic ester fluids as their relative humidity is increased from 5% (‘dry’ fluid) to 30%. Testing of the fluids was conducted under AC and impulse voltage stress, with AC breakdown performed in accordance with ASTM D1816 standard (gap spacing of 1mm) while the impulse breakdown tests conformed to the ASTM D3300 procedure in sphere-sphere electrode configuration (sphere diameter = 12.7mm, gap spacing of 3.8mm).



(a) (b)

Figure 2-24; *The effect of relative humidity on (a) AC and (b) lightning impulse breakdown voltage of synthetic ester, natural ester and mineral oil. Experimental data taken from [96].*

When under AC voltage stress both the natural and synthetic ester fluids have a higher dielectric strength than the investigated mineral oil when in a heightened state of relative humidity, while offering a similar performance in the low humidity condition. As can be seen in Figure 2-24a, there is overlap in the breakdown voltage error bars (which represent the values of standard deviation in the breakdown voltage) for both ester fluids for the relative moisture content 5% and above, indicating similar breakdown voltages for the ester fluids. The breakdown strength of mineral oil is lower than that of both ester fluids for the relative moisture content >10%. This difference in breakdown strength of the ester fluids and mineral oil increases with an increase in the level of relative humidity of these liquids. Both the synthetic and natural ester fluids show no discernible reduction in breakdown voltage as relative humidity is increase; this is not the case for the tested mineral oil which exhibits a stark reduction in breakdown voltage between the ‘dry’ and 30% relative humidity levels (~48%).

When the same liquids are tested under impulse voltage, it is the mineral oil which is seen to possess the higher breakdown strength when in the ‘dry’ condition. However, this high breakdown strength rapidly decreases as the level of relative humidity is increased to a point where at the highest level of relative humidity investigated (RH ~30%) the mineral oil has lowest breakdown strength of the three fluids. As with the tests conducted under AC voltage, both the natural and synthetic ester fluids show no clear trend in breakdown voltage as relative humidity of the fluid is increased.

2.6. Impulse breakdown of composite liquid-solid insulating systems

Composite liquid-solid insulating systems are commonly implemented within large electrical machines either to limit the flow of electrical current between electrodes or to provide mechanical support of internal structures of the machine. The most prevalent use of such an insulating system is within electrical transformers where Kraft paper, used as winding insulation, is immersed in volume insulating dielectric liquid; commonly mineral oil. Thus, breakdown testing of liquid-solid composite systems is typically conducted under conditions to mimic the operational electrical stress experienced by a transformer. However, as liquid-solid composite insulation also exists within pulsed power machines it is important to evaluate the breakdown characteristics of such insulating systems under non-standard voltage stress.

2.6.1. Breakdown mechanisms of liquid-solid composite insulation

As with bulk liquid, and solid, breakdown the predominate breakdown mechanism of the liquid-solid interface of composite insulation under impulse voltage stress is one of ionisation front, streamer, development. This was confirmed by Cherney and Cross in [97], where the authors examined the breakdown behaviour of liquid-solid insulation comprising of a Teflon spacer submerged in mineral oil under uniform electric field. When stressed with a combination of DC and impulse (1.5/50µs) voltage simultaneously it was observed that the composite samples could withstand voltage stress 95% that of the DC flashover strength of the insulation. This observation led the authors to conclude that differing breakdown mechanisms exist for DC and impulse breakdown of liquid-solid composite insulation; with DC breakdown occurring due to a process of bubble formation while breakdown under impulse voltage happened as a result of cavitation and electron acceleration as described in Section 2.3.3.

2.6.2. Triple junction effect

It was established in [98] that the presence of metal-solid-liquid triple junctions have a marked effect on the breakdown performance of liquid-solid composite insulation. This is as a consequence of the occurrence of two differing phenomena; either charge accumulation at the liquid-solid interface or the existence of a gap between the energised electrode and the solid dielectric. If either of these situations are to arise it will result in a distortion of the electric field in the vicinity of the energised electrode. Cross in [98] discusses the effect on the electric field distribution in the system when a gap is present between the electrode and solid spacer; in such circumstances the field developed in the gap can be described thusly:

$$E_{Gap} = E_0 \left(\frac{\varepsilon_s}{\varepsilon_l}\right) \qquad (2\text{-}4)$$

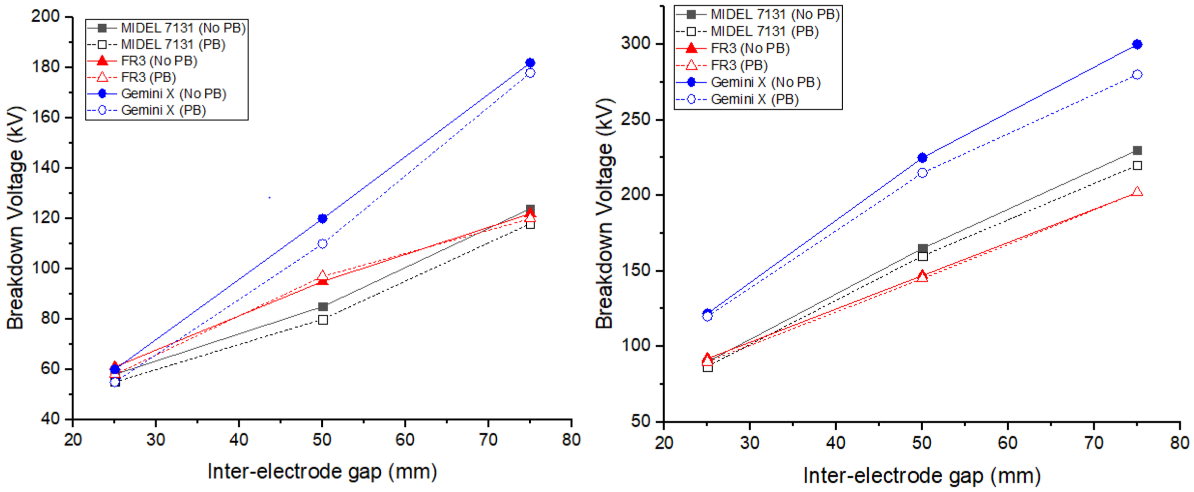
where ε_s and ε_l are the relative permittivity of the solid and liquid dielectrics respectively and E_0 is the magnitude of the externally applied electric field when unaffected by the triple junction.

As is apparent for equation 2-4, when the permittivity of the solid dielectric is much greater than that of the liquid a significant increase in local electric field magnitude in the vicinity of the triple junction will occur; this is of concern in transformer insulating systems where permittivity of the solid insulation media (Kraft paper) is almost twice that of the surrounding insulating oil (4.2 as compared with 2.2). Cross goes on in [98] to state that any experienced distortion in the electric field will be worsened if any defects, such as gas-filled voids, are present within the structure of the solid dielectric.

The effect of this triple junction on the breakdown of polymer insulation was also investigated by Hammam et al. in [99]. The authors tested HDPE insulation under positive and negative lightning impulse (1.2/50μs) with the insulation surrounded by both wet and dry air. It was observed during experimental work that the 50% probability of flashover voltage for the polymers under negative energisation when in dry air was higher than that of samples in a moist environment. It was postulated by Hammam et al that this higher breakdown strength observed for the dry samples was as a result of charge accumulation at the triple junction causing a dampening of the electric field in this area and thus an inability to reach the threshold required for development of breakdown streamers. The same situation did not occur in the wet environment due to a reduction in electron attachment at the liquid-polymer interface mitigating the effect of charge accumulation on the electric field developed at the triple junction. When under positive impulse stress the aforementioned charge accumulation phenomenon does not occur, with electrons attracted to the anode, and thus there was almost no discernible difference in flashover voltage for the wet and dry polymer samples.

2.6.3. The effect of impulse polarity on breakdown across liquid-solid interfaces

As is clear from the work conducted by Hammam et al [99] discussed in the preceding section, the impulse polarity has a direct influence on the breakdown performance of liquid-solid composite insulation. Efforts to quantify the effect of impulse polarity on the flashover behaviour of composite insulation were made by Liu and Wang in [100] where the authors investigated the breakdown of ester-paper insulation. The work undertaken involved the testing of natural ester Envirotemp FR3, synthetic ester MIDEL 7131 and mineral oil Gemini X when acting in conjunction with solid insulation in the form of pressboard when under highly divergent electric field conditions. The experimental procedure applied saw liquid-solid samples stressed with dual polarity lightning impulse voltages in point-plane electrode configuration (tip radius = 50μm, gap spacing 25mm to 75mm). Liu and Wang configured their test cell in such a way that the electrodes are orientated parallel to, while in direct contact with, the pressboard samples. Further to the testing of the flashover performance of the liquid-solid composite samples, Liu and Wang also evaluated what effect the presence of the solid dielectric had on breakdown behaviour by conducting tests in which the pressboard was removed from the inter-electrode gap and comparing results to those gathered for the liquid-solid samples.



(a) (b)

Figure 2-25; *Lightning impulse breakdown voltage of synthetic ester MIDEL 7131, natural ester Envirotemp FR3 and mineral oil Gemini X both with and without pressboard interface under (a) positive and (b) negative energisation. Experimental data taken from [100].*

From the work Liu and Wang conducted in [100] (Figure 2-25a and 2-25b) they determined that under positive impulse stress the inclusion of a pressboard insulator has little to no effect on the breakdown voltage of either natural ester, synthetic ester or mineral oil at any of the tested inter-electrode gap distances. At the shortest gap used (25mm) all three insulating liquids demonstrate comparable levels of dielectric strength, this however changes with an increase in inter-electrode gap where mineral oil breakdown voltage becomes higher than that of both ester fluids. This difference is seen to be at maxima when the inter-electrode gap is at its widest (75mm). Irrespectively of gap distance, both ester fluids are observed to have comparable levels of breakdown voltage.

Under negative impulse, the ester liquids again exhibit comparable levels of dielectric strength for all gap distances. Although unlike the behaviour observed under positive impulse, mineral oil now consistently experiences breakdown at higher levels of voltage than the ester fluids even at the short (25mm) gap distance. The inclusion of the pressboard dielectric again has no influence on the breakdown voltage of the natural or synthetic ester fluids, though an effect is observed in the breakdown results gathered for the mineral oil. A reduction in breakdown voltage of the mineral oil samples is seen to occur at all inter-electrode gaps with breakdown voltage as much as 20kV lower when the pressboard is present (75mm gap). The authors attribute this to a pre-stressing effect on the interface resulting as a consequence of the specific method used to achieve breakdown. As a step voltage methodology is used in tests, voltage stress is applied a number of times before breakdown actually occurs which the authors assumed caused pre-stressing of the interface leading to charge accumulation and increasing the susceptibility for breakdown. This hypothesis was confirmed by the authors by conducting tests where the pressboard was changed after each voltage application, rather than after each breakdown, after which the breakdown voltage of the mineral oil with and without the inclusion of pressboard were identical.

2.6.4. The influence of the solid dielectric structure on breakdown

The composition of the solid dielectric within a liquid-solid composite insulating system can exert influence on the breakdown behaviour of the insulating system. It is therefore important to understand the effect defects and irregularities in the structure of the solid media can have on the overall dielectric strength of the liquid-solid composite. Lerchbacher et al. [101] investigated the influence small gas-filled voids present within the solid dielectric exert on the partial discharge behaviour of epoxy resin samples. The authors determined that samples with the addition of artificial inclusions experienced a lower level of partial discharge voltage than those samples absent of voids. This behaviour can be attributed the breakdown of the gas within the voids occurring at a lower level of voltage than that of the bulk solid material. Upon application of a sufficiently high energisation voltage partial discharge occurs in the gas contained within the voids and eventually complete breakdown of the void is initiated; lowering the overall dielectric strength of the solid insulation.

Another factor associated with the properties of the solid dielectric which can negatively affect the breakdown strength of any liquid-solid composite is the degree of surface roughness of the solid dielectric. This effect was studied by Krins et al. in [102] where five solid dielectric materials of varying surface roughness were tested under lightning impulse voltage of both positive and negative polarity. When under negative energisation the specific degree of surface roughness was observed to exert a direct influence on breakdown voltage; with the roughest samples possessing the lowest breakdown strength. This effect occurs as a consequence of local field enhancement on the surface of the solid dielectric due to micro-protrusions. This leads to increased generation of charges within the oil volume in the vicinity of the solid surface, as described in Section 2.3.3, as well as secondary emission of electrons from the surface of the solid dielectric. No such effect is observed when the samples are under positive impulse stress due to the differing mechanism responsible for breakdown under such energisation polarity; namely, pseudo-extension of the anode as discussed in Section 2.3.3.

2.6.5. The effect of mismatch in relative permittivities on breakdown characteristics

When a difference in relative permittivity exists between the solid and liquid components of a composite insulating system it can result in detrimental effects to the dielectric performance. The effect of mismatches in permittivity was investigated by Taylor in [103] where the degree of mismatch is described in terms of the "interfacial permittivity ratio" derived as follows:

$$Interfacial\ permittivity\ ratio = \frac{\varepsilon_{Liquid}}{\varepsilon_{Solid}} \tag{2-5}$$

During the study a number of solid dielectric materials of varying relative permittivity (ε_r = 2–5) were immersed in transformer oil, as well as other dielectric liquids including silicone oil and Anchor PCB liquid, and subjected to positive polarity pseudo-impulse voltage when under uniform field stress (plane-plane configuration). Taylor discovered that the interfacial permittivity ratio of a particular liquid-solid composite has an influence on the level of breakdown voltage observed. In the case when this ratio is <1, i.e. the permittivity of the solid is greater than that of the liquid, a reduction in breakdown voltage occurred as compared to that of the bulk liquid. Taylor attributed this to an enhancement of the electric field in the vicinity of the surface of the solid dielectric arising from surface irregularities such as micro-protrusions; similar to the effect discussed in Section 2.7.5. When the inverse is true and the interfacial permittivity ratio is >1 a small reduction in breakdown voltage was observed for some of the tested liquid-solid composites as compared with the bulk liquid insulation, though to a much lesser extent than when the ratio is <1; with breakdown voltage of the any of the composite systems never falling below 90% of that of the bulk liquid insulation, even at ratios as high as 1.87 where relative permittivity of the liquid is almost twice that of the solid dielectric.

The effect of relative permittivity mismatch was also investigated by Anker et al in [104], though unlike Taylor's work [103], this study was conducted in divergent field conditions using a rod-plane electrode configuration. Solid samples of permittivity 2.3, 4.1, 4.3 and 4.6 were submerged in transformer oil (relative permittivity 2.28) and stressed with 1/50µs positive impulse voltage. Anker et al. observed very similar breakdown behaviour to that of Taylor; i.e. when the permittivity of the solid is higher than that of the liquid a reduction in breakdown strength was observed, with this worsening with an increase in the level of mismatch. Again, this was attributed to field enhancement occurring on the surface of the solid dielectric as a result of asperities protruding from the solid dielectric.

2.6.6. The effect of impulse rise-time on breakdown characteristics

Given that the specific characteristics of the impulse applied to bulk insulating liquids has been shown to directly influence dielectric performance, as discussed in Section 2.4.4, it is important to understand what effect the impulse rise-time parameter has on the breakdown of liquid-solid composite systems.

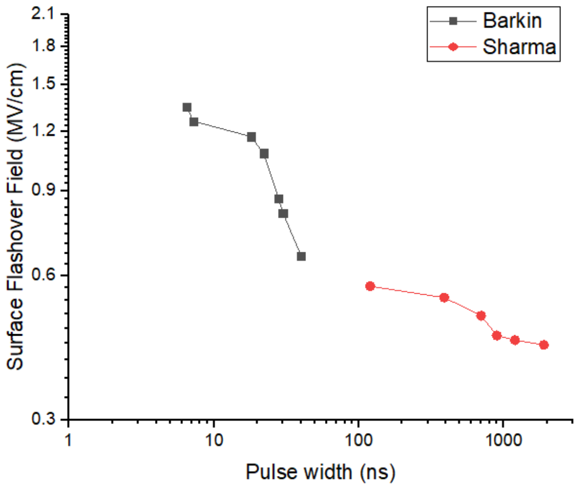


Figure 2-26; *The effect of impulse width on the field magnitude required to cause surface flashover of mineral oil-PMMA interface. Experimental data taken from [105]-[107].*

Work to quantify the effect of the pulse width on the flashover performance of polymers immersed in transformer oil was conducted by Sharma [105], [106] and Barkin [107] where both authors independently tested samples of PMMA placed between plane-plane electrodes and submerged in transformer oil using a range of impulse voltages. From their results, summarised in Figure 2-26, it is apparent that the width of the voltage impulse has a direct influence over the flashover strength of the liquid-solid interface. As the width of the pulse is increased there is a clear reduction in the level of field strength required to cause flashover of the liquid-PMMA interface.

The effect of pulse width on the breakdown of liquid-polymer interfaces was also investigated by Zhao et al in [108]. Their work involved stressing samples of PMMA and Nylon 6 with a number of short impulses with the aim to derive a "critical pulse width" at which the behaviour of the composite system would favour a particular type of breakdown; be that bulk breakdown of the polymer or flashover of the liquid-polymer interface.

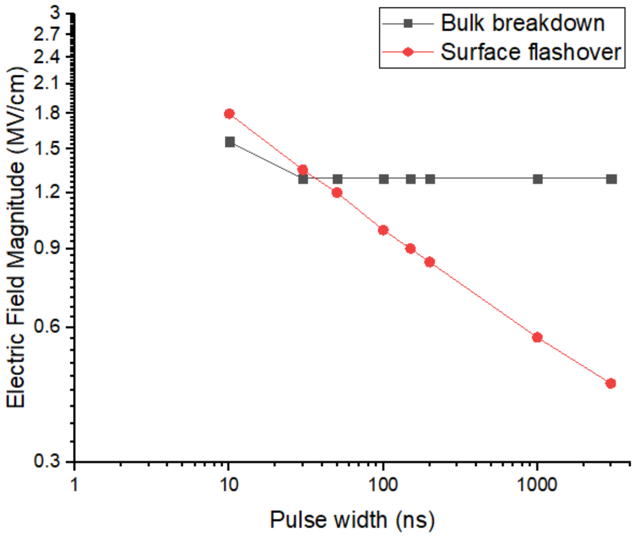


Figure 2-27; *The effect of impulse width on the field magnitude required to cause either surface flashover of mineral oil-PMMA interface or bulk breakdown of the polymer. Experimental data taken from [108].*

Zhao et al. show that at a critical pulse width, 33ns in the case illustrated in Figure 2-27, the magnitude of electric field required to initiate surface flashover falls below that necessary to cause bulk breakdown of the polymer dielectric. As with the results reported by [105]-[107], flashover field is seen to reduce as the width of the pulse is increased. Interestingly though, the magnitude of electric field required to cause bulk breakdown of the polymer remains constant over the large range of pulse widths used by Zhao providing the pulse width has exceeded the critical width (33ns to 3µs).

2.7. Use of ester fluids within electrical equipment

The application of vegetable-based dielectric fluids within large electrical machines and equipment has been suggested since the early 1980s. The first use of such fluids was as a replacement for PCBs within large capacitors where castor oils were shown to be a viable alternative to toxic PCBs for polypropylene and polypropylene-paper capacitors [109].

Since this early work other vegetable-based fluids, such as natural and synthetic ester liquids, have been adopted for use within both medium and high voltage transformers; with the first natural ester filled power transformers in operation from 1996 [3]. Following this initial implementation, the number of natural ester filled transformers has grown significantly to ~600,000 units operating worldwide across distribution and power class machines [3]; currently the largest of these is 420kV unit installed in Baden-Wuttenburg, Germany. The machine, filled with Envirotemp FR3 natural ester fluid has operated continuously at a level of 300MVA without any reported issues since its commissioning in 2014 [3].

Synthetic ester fluids have been used within transformers for a significantly longer time than their natural counterparts, operating for more than thirty years within medium voltage units [110]. As of 2008 there were 114 medium voltage transformers (11kV) filled with synthetic ester MIDEL 7131 operating within the Scottish Power energy network; growing considerably from the previous year where only 4 units were present in the network [111]. This stark rise in the number of units within the network was attributed by Scottish Power to the clear safety benefits offered by synthetic ester fluid as compared with conventional mineral oil. Consequently, the network operator took the decision to expand the use of MIDEL 7131 filled transformers to include 33kV units, of which 15 are currently operating within the network. The excellent performance of these medium voltage units led Scottish Power to implement synthetic ester filled transformers at the high voltage level, commissioning their first 132/33kV unit in 2017 and expanding to a total of 8 similar sized units today [111].

While the aforementioned adoption of natural and synthetic ester fluids within the power industry clear demonstrates their adequacy as an alternative to conventional mineral oil at medium and high voltage levels it does not extend to pulsed power machines. This lack of acceptance of ester fluids within the pulsed power industry is due to the absence of suitable data on the dielectric performance of both natural and synthetic ester fluids when operating in conditions representative of the typical electrical stresses placed on pulsed power apparatus.

It is therefore the intention of the work presented in this thesis to increase the confidence in the viability of ester fluids to operate in such machines. This will be achieved through a comprehensive experimental investigation of the breakdown behaviour of both natural and synthetic ester fluids, as well as ester-polymer composite insulating systems, under testing conditions representative of electrical stress experienced by in-service pulsed power machines; i.e. application of non-standard impulse voltages in highly divergent electric field conditions under both positive and negative energisation. To that end, a laboratory investigation was conducted during which a number of discrete voltage impulses were used throughout the experimental work undertaken to mirror the electric stress experienced within large pulsed power machines while also providing data to inform operators of power system assets such as transformers. All experimental data relating to the breakdown of the ester insulating fluids and ester fluid-polymer composite systems was evaluated against mineral oil-based insulating systems tested under identical experimental conditions.

Chapter 3 – Experimental setup, sample conditioning and testing methodologies

3.1. Introduction

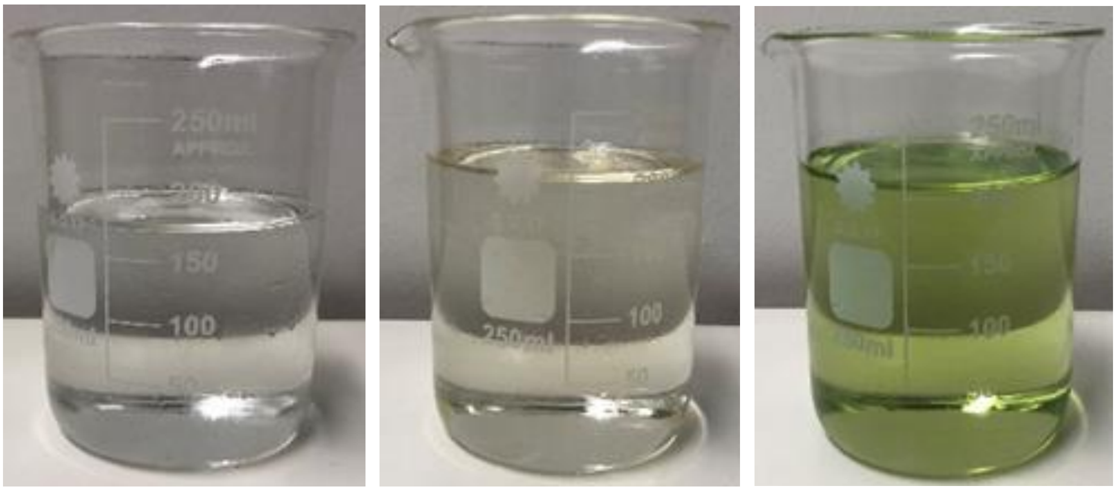
The proceeding chapter will outline all materials and equipment utilised within the experimental investigation into the bulk and interfacial breakdown of ester dielectric fluids under impulse voltage stress. This extends to description of all dielectric materials used, both liquid and solid, conditioning of test samples, experimental setup used to produce the required high voltage impulses, associated diagnostic devices, and test cells used. Further to this, the analytical and testing methodologies used in both the bulk breakdown and interfacial breakdown studies will also be described in detail.

3.2. Dielectric materials used in experimental work

As the work detailed in this thesis involved the study of both bulk liquid and liquid-solid interfacial breakdown of ester fluids and mineral oil a number of liquid and solid dielectrics were used. The following sections will describe these in detail, outlining all key operational parameters.

3.2.1. Liquid dielectrics used in experimental work

Within the experimental studies detailed within this thesis three dielectric fluids were consistently used. The first of these was a naphthenic-based mineral oil Shell Diala S4 (Shell Ltd, UK), with this fluid used as means of benchmarking the performance of conventional transformer liquid insulation. The remaining two dielectric fluids investigated were a synthetic ester MIDEL 7131 (M&I Materials Ltd, UK) and a natural ester Envirotemp FR3 (Cargill Ltd, USA). These ester–based dielectric fluids were selected as they are currently being used within both distribution and power transformers [2], [112], [113] and have been shown under laboratory testing conditions to offer similar dielectric performance to conventional mineral insulating oils [5], [6]. Therefore, they may offer a viable alternative to the use of mineral oil insulation within large pulsed power machines.



(a) (b) (c)

Figure 3-1; *Dielectric fluids used in experimental studies; (a) mineral oil Shell Diala S4; (b) synthetic ester MIDEL 7131; (c) natural ester Envirotemp FR3*

The chosen mineral oil, Shell Diala S4 is clear and colourless (Figure 3-1a). This inhibited mineral oil is manufactured using a gas-to-liquid process and is sulphur free meaning it is less corrosive to copper than other conventional transformer oils [114]. The synthetic ester fluid MIDEL 7131 has a light-yellow colouration and is transparent (Figure 3-1b). This fluid is derived from a formulation of C5:10 Pentaerythritol tetra esters (>99.5%) and performance enhancing additives (<0.5%) [115]. The chosen natural ester liquid, Envirotemp FR3, is light green in colour and mildly transparent (Figure 3-1c). This fluid is manufactured from soybean oil (95%) and unnamed additives (5%) [116] and is free from halogens, petroleum and sulphur [116]. Key physical, chemical and electrical parameters of the three investigated dielectric fluids have been summarised in Table 3-1.

Table 3-1; *Key physical, chemical and electrical parameters of chosen dielectric fluids. Taken from [114]-[116]*

Properties	Unit	Shell Diala S4	MIDEL 7131	Envirotemp FR3
Physical properties				
Density at 20°C	kg/dm^3	0.81	0.97	0.92
Specific Heat at 20°C	J/kg K	1860	1880	1848
Thermal conductivity at 20°C	W/m K	0.126	0.144	0.177
Kinetic viscosity at 40°C	mm^2/s	9.6	29	33
Pour point	°C	-42	-56	-20
Flash point	°C	191	260	270
Fire point	°C	220	316	360
Water saturation	ppm	70	2600	1100
Biodegradability at 28 days	%	89	<10	97
Chemical properties				
Composition	N/A	Mix of hydrocarbons	Pentaerythritol tetra esters	Plant-based ester
Acidity	mg KOH/g	0.02	0.02	0.01
Total sludge	% mass	<0.01	<0.01	Not Given
Electrical properties				
Breakdown voltage (50Hz)	kV	60	>75	>55
Dissipation factor (tan δ) at 90°C	N/A	0.001	<0.008	0.02
Permittivity (@ 1MHz)	N/A	2.2	3.2	3.2
Conductivity at 25°C	S/m	$\sim 1e^{-13}$	$\sim 1e^{-12}$	$0.5e^{-12}$

When examining the physical properties of the three dielectric fluids it becomes apparent that ester fluids, both natural and synthetic, offer a number of important benefits as compared with conventional naphthenic-based mineral oil. One such benefit is the higher thermal conductivity of ester fluid which can aid in machine cooling, which is a key criterion of any volume insulator; though the increased viscosity of the fluids may counteract this through a reduced flowrate. Operational benefits can also be realised through the use of ester fluids in large electrical machines as a result of their much greater waster saturation levels; with natural and synthetic ester able to tolerate ~16 and ~37 times more water respectively than conventional mineral oil. This property of ester fluids can prove to be highly advantageous given the well documented detrimental effect of moisture on the dielectric strength of insulating fluids [9], [10], [92], [93], [96]. This attribute of ester fluids to accommodate higher levels of moisture than mineral oil has also been shown experimentally to slow the degradation of cellulose paper and increase the lifespan of the paper insulation [117]-[120].

Improvements to operational safety can also be achieved with the use of ester-based dielectric fluids. Both the flash and fire points of natural and synthetic ester fluid are considerably higher than that of conventional mineral oil; therefore, reducing the potential for catastrophic failure of the machine from fire or explosion which is a problem for oil-filled transformers [121]. This reduced fire risk can also facilitate an increase in the ability of machines to operate in hazardous environments where ignition risk must be minimised. Environmental safety is also improved with the use of ester fluids due to their increased biodegradability and much lower toxicity than mineral oils. This will allow for machines filled with ester fluids to operate in locations where the risk of potential leakage into the environment would otherwise prohibit machine placement were the apparatus to contain mineral oil; such as areas of environmental conservation.

There are however some concerns when implementing ester-based dielectrics in place of conventional mineral oil. One of which is the higher pour point of ester fluids, particularly natural ester, which can restrict the ability of these fluids to operate effectively in extremely cold environments where temperatures are routinely below -20°C. Another issue surrounding the use of ester dielectric liquids is the higher levels of electrical conductivity they possess; which may lead to higher leakage current into the dielectric, increased initial space charge and encourage development of breakdown streamers [13].

3.2.2. Solid dielectrics used in experimental work

During the work to characterise the breakdown of ester-polymer interfaces five individual solid polymers were placed in direct contact with the dielectric fluids discussed in Section 3.2.1. These polymers were selected to reflect the types of materials currently used, or proposed to be used, in large electrical machines and pulsed power apparatus. Further to this, as these materials possess values of relative permittivity both above and below that of the chosen dielectric fluids their selection will allow for the evaluation of how varying levels of permittivity mismatch may affect the dielectric performance of ester-polymer composite insulation systems. The key parameters of the chosen polymers; Nylon 6,6, polymethyl methacrylate (PMMA), polyoxymethylene (DELRIN) and polyamide-imide (TORLON), have been summarised in Table 3-2.

Table 3-2; *Key operational parameters of solid dielectric materials used in experimental study. Taken from [122]-[125]*

Properties	Unit	Nylon 6,6	PMMA	TORLON	DELRIN
Composition	N/A	Polyamide	Polymethyl-Metacrylate	Polyamide-imide	Polyoxymethylene
Density	g/cm³	1.14	1.19	1.46	1.42
Dielectric Strength (AC)	kV/mm	27	20	23	20
Relative Permittivity (MHz)	N/A	3.8	2.6	4.2	3.7
Tensile strength	MPa	82	80	110-190	70
Volume resistivity	Ω/cm	$5e^{13}$	$8e^{14}$	$\sim 1e^{17}$	$1e^{15}$
Volume conductivity	S/cm	$2e^{-14}$	$1.25e^{-15}$	$1e^{-17}$	$1e^{-15}$
Surface resistivity	Ω/sq	$5e^{11}$	$1e^{14}$	$\sim 30e^{17}$	$1e^{15}$
Surface conductivity	S/sq	$2e^{-12}$	$1e^{-14}$	$3.33e^{-19}$	$1e^{-15}$
Dissipation factor (MHz)	N/A	.2	0.014	0.038	0.010
Water absorption	%	8	2	3.5	0.7

When examining the parameters of the polymer dielectrics, provided in Table 3-2, it is clear that all selected materials offer very similar levels of dielectric strength when under power frequency AC voltage stress. Given that during the work presented in this thesis the samples will be stressed with a number of impulse voltages it is to be assumed that this characteristic will not be the same and is only included for means of comparison. One parameter which does differ between polymers is the surface and volume resistivity and thus the inverse of this parameter, conductivity. Surface conductivity can be seen to differ by more than 6 orders of magnitude when comparing the most extreme case; that of the Nylon 6,6 and TORLON polymers. This should result in dissimilarity in the flashover behaviour of these materials, with samples of higher surface conductivity possessing increased likelihood of surface flashover. Interestingly the TORLON polymer is the only material which possesses a volume conductivity which is higher, ~2 orders of magnitude, than surface conductivity. The water absorption parameter has been included in Table 3-2 as a means of quantifying the level of porosity of the polymers, while this cannot be assumed to indicate the absolute level of porosity, given factors such as voids within the sample created during the manufacturing process, it does act as a means of comparing one polymer to the next. A clear difference in porosity does exist, with samples of the DELRIN polymer assumed to be much less porous than that of the Nylon 6,6 polymer; assumed due the one order of magnitude increase in water absorption of the Nylon 6,6 as compared with the DELRIN material.

3.3. Sample conditioning

As all dielectric materials used within the experimental studies conducted in this thesis were provided from manufactures in an 'As received' condition a process of sample preparation was required to ensure their adequacy for use during testing. In the case of the liquid dielectrics this involved control of the water content of the liquid samples and removal of any gas bubbles present. Solid dielectrics required sizing and treatment to the surface of the polymer to ensure sample consistency. Further details of the liquid and solid sample conditioning will be provided in the following section.

3.3.1. Conditioning of liquid dielectric samples

As one of the main aims of the work detailed in this thesis was to investigate how the absolute water content of the dielectric fluid affected breakdown performance under impulse voltage stress there was a requirement to control the relative humidity of each of the liquid samples. During the experimental work three discrete levels of relative humidity were examined; the first was fluids in the 'As received' conditions (lowest RH) with relative humidity as provided by the manufacturer. To achieve the next level of relative humidity, 'Ambient level', liquid samples were placed in open containers for ~2 months to allow the relative humidity to reach an equilibrium with that of ambient laboratory conditions. The final level of relative humidity, termed 'Elevated level' represents the highest level of relative humidity examined and was achieved through a humidification process. The levels of relative humidity, as well as the absolute water content, for each examined liquid state have been given in Table 3-3.

Table 3-3; *Discrete levels of dielectric liquid relative humidity used in experimental study. Absolute moisture content calcuated based on water satuartion levels stated in manufacturer datasheets [114]-[116]*

Liquid	As Received		Ambient Level		Elevated Level	
	RH%	ppm	RH%	Ppm	RH%	ppm
Shell Diala S4	21	15	35	25	70	49
MIDEL 7131	12.5	325	34	884	72	1872
Envirotemp FR3	9	99	34	374	73	803

As is apparent from the data in Table 3-3, both ester fluids can accommodate a considerably higher amount of moisture for a given level of relative humidity than the mineral oil. The synthetic ester MIDEL 7131 can hold the highest levels of moisture for a given state of relative humidity as a result of its extremely high saturation point ~2600ppm. As aforementioned to achieve the highest examined level of relative humidity the liquid samples were subjected to a humidification process. This allowed for the moisture content of the fluid to be increased considerably over a relatively short time.

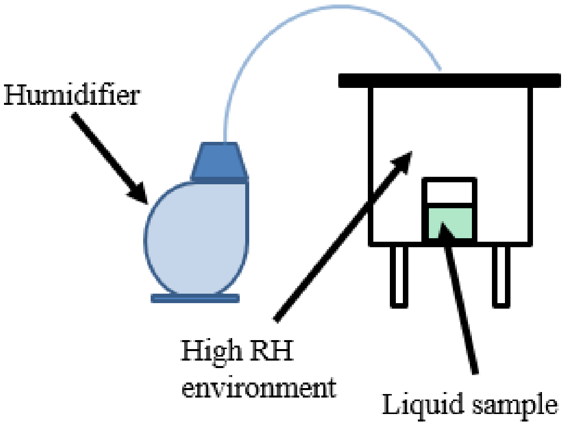


Figure 3-2; Schematic of system used to increase the humidity of liquid samples to 'Elevated' level

During this humidification process liquid samples were placed within a sealed chamber into which a water mist was fed from an ultrasonic humidifier. Within the chamber relative humidity was maintained continually at a level of 90-95%, which allowed for sample humidity to reach the desired level of relative humidity corresponding with that set for the 'Elevated level' state within a short period of time; detailed in Table 3-4.

Table 3-4; *Uptake time for each dielectric liquid to reach Elevated level of relative humidity*

Liquid	Entry RH%	Exit RH%	Time taken
Shell Diala S4	~20	70	~1 day
MIDEL 7131	~12	72	~11 days
Envirotemp FR3	~10	73	~4 days

From Table 3-4 which provides the uptake time for each dielectric liquid to reach the ‘Elevated level’ of relative humidity it is clear that both ester fluids required more time within the humidification chamber than the mineral oil. This is to be expected given the much higher water saturation limits of the ester fluids compared to the mineral oil. Interestingly the uptake time does not show a linear relationship, with the natural ester only requiring 4 times longer in the chamber than the mineral oil to reach the ‘Elevated level’ state despite having a ~16 times higher water saturation limit than the mineral oil. This is also the case for the synthetic ester which remained in the high humidity environment 11 times longer than the mineral oil with a saturation limit ~37 times larger.

Figure 3-3; *Omiport 20 oil humidity and temperature probe used to measure relative humidity of the dielectric fluids*

Throughout all bulk liquid breakdown experimentation, the relative humidity of liquid samples was monitored using a commercially available humidity sensor; Omiport 20 humidity and temperature probe. Measurements of the relative humidity of the liquid samples were taken at two points during testing; one reading was taken before the liquid was poured into the breakdown test cell to ensure the appropriate level of relative humidity had been achieved, with another taken after degassing of the liquid to ensure no moisture had been lost during this process.

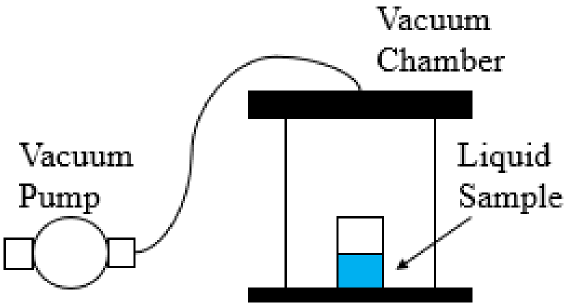
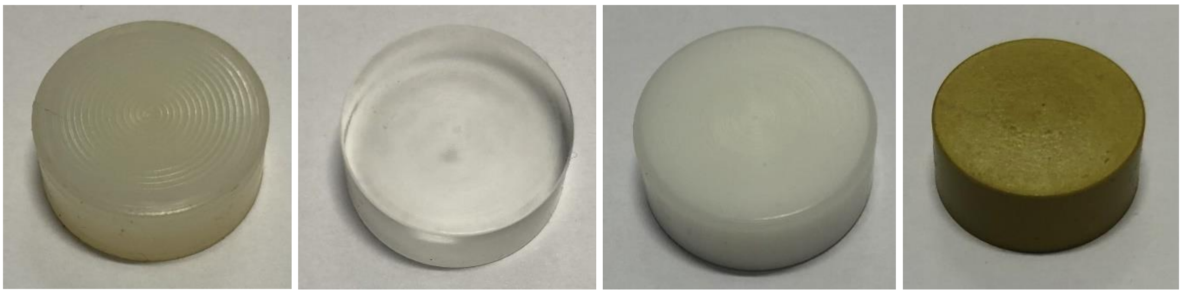


Figure 3-4; *Schematic of vacuum systems used to degas dielectric liquids prior to tests.*

Given the well documented detrimental effect pre-existing vapour bubbles present in the dielectric liquid have on breakdown strength [126]-[128] it is of great importance to remove these prior to conducting any experimental work. Removal of such gas bubbles within the volume of the dielectric samples prior to tests was assured through the use of a degassing process. This involved placing liquid samples within an airtight cylindrical chamber connected to an N813 Series diaphragm vacuum pump (ultimate vacuum ~0.5mbar). Once samples were inside the chamber the internal pressure of the chamber was dropped as close as possible to 0 bar (pure vacuum). Samples then remained within the chamber for thirty minutes, chosen after reviewing similar dielectric liquid tests published in literature [11], [18], [129]. The chosen time proved to be more than adequate to remove all visible bubbles present within the fluid. As aforementioned to ensure this degassing process did not affect the moisture content of the fluid a second measurement of relative humidity was performed upon removal of the liquid sample from the chamber. This degassing procedure was performed on all liquid samples prior to bulk breakdown testing and all liquid-solid composite samples before interfacial flashover tests.

3.3.2. Conditioning of solid dielectric samples

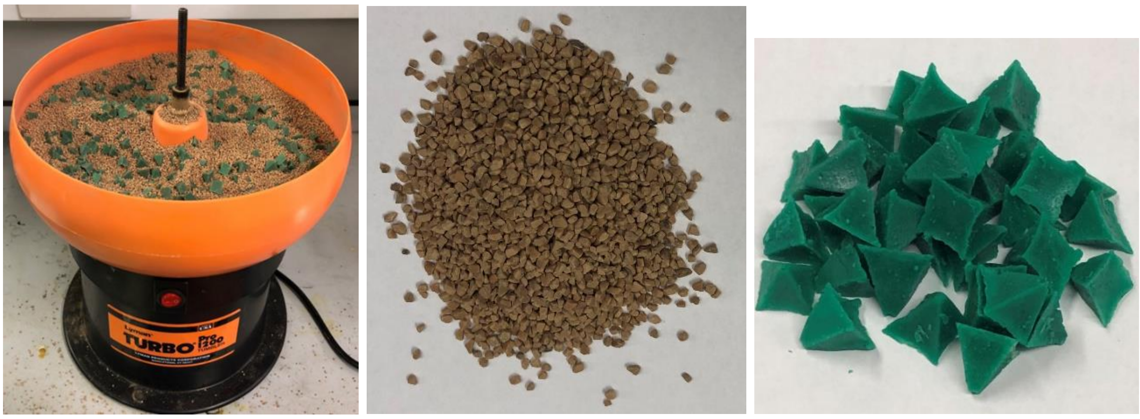
As the polymer dielectric materials were sourced from commercial manufactures they were supplied as rods of varying length (2-3m) which required samples to be machined to a desired shape and length. The decision was taken to use puck shaped samples (diameter 20mm, thickness 8mm) in order to mitigate any possible field enhancement that may occur at the sample edge due to fringing effects.



(a) *(b)* *(c)* *(d)*

Figure 3-5; *Solid dielectric samples used in experimental study; (a) Nylon 6,6; (b) PMMA; (c) DELRIN; and (d) TORLON.*

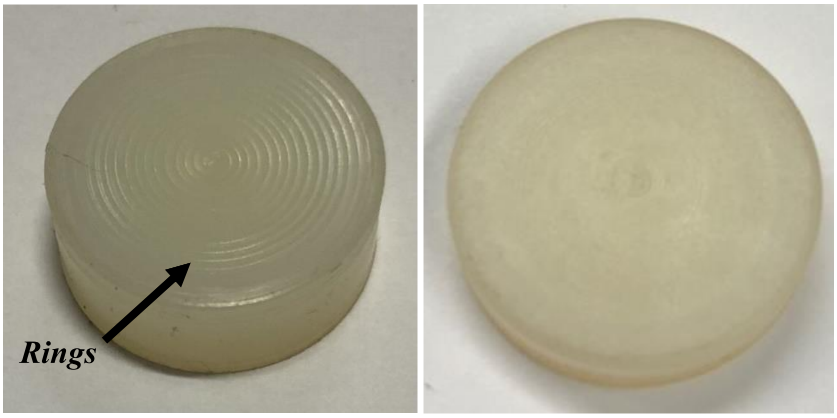
Sample thickness was set at 8mm to present the best compromise between ensuring the bulk breakdown strength of the polymer was maintained while allowing a suitably short propagating path to ground for any developed breakdown streamers across the surface of the polymer. Due to the specific machining processes used to manufacture the polymer samples a number of visible 'rings' were left on both faces of the dielectric samples; thus a process of 'polishing' was introduced to remove these 'rings' and mitigate any effects such asperities may exert of the breakdown behaviour of the liquid-solid composite systems.



(a) (b) (c)

Figure 3-6; *Depiction of (a) Vibrating tumbler; (b) walnut shell; (c) plastic pyramid polishing media, used in the smoothing of solid dielectric samples.*

The specific polishing process used to ensure the removal of manufacturing rings and other asperities from the polymer samples was one of vibrational polishing. This involved placing samples into a large tumbler along with two types of polishing media; one soft and one hard. The soft material selected for use was walnut shell, while the hard media was in the form of small plastic pyramids. The decision to use a combination of both hard and soft, as well as the specific concentration of each, polishing materials was made after a number of preliminary tests had shown that one single material would not adequately remove the asperities. When tests were conducted with just the walnut shell rings were still present on the surface of samples even after several days of treatment, while tests involving only the hard pyramids resulted in damage to the surface of the polymer and an increase in asperities. Thus, it became apparent that a combination of each polish medium would offer optimum asperity removal.



(a) (b)

Figure 3-7; *Depiction of Nylon 6,6 sample (a) with visible post-manufacture 'rings' on the surface and (b) with all 'rings' removed after treatment in tumbler.*

An example of a Nylon 6,6 sample before and after 24hrs of treatment within the tumbler can be seen in Figure 3-7. The rings present on the surface of the sample (Figure 3-7a) have been completely removed (Figure 3-7b) after treatment. This removal of asperities, checked visually post-polishing, not only ensured the mitigation of any field enhancement which may originate from such points on the sample surface but also maintained a comparable level of surface roughness for all polymer samples.

3.4 Experimental setup used during breakdown tests

The proceeding sections will be used to describe in its entirety the testing system employed during all breakdown experimentation. This will include the pulsed power circuit used to generate high voltage impulses, associated diagnostics system, and the individual test cells utilised for bulk liquid and liquid-solid breakdown experimentation. The testing setup used in the bulk breakdown experimentation is depicted in Figure 3-8.

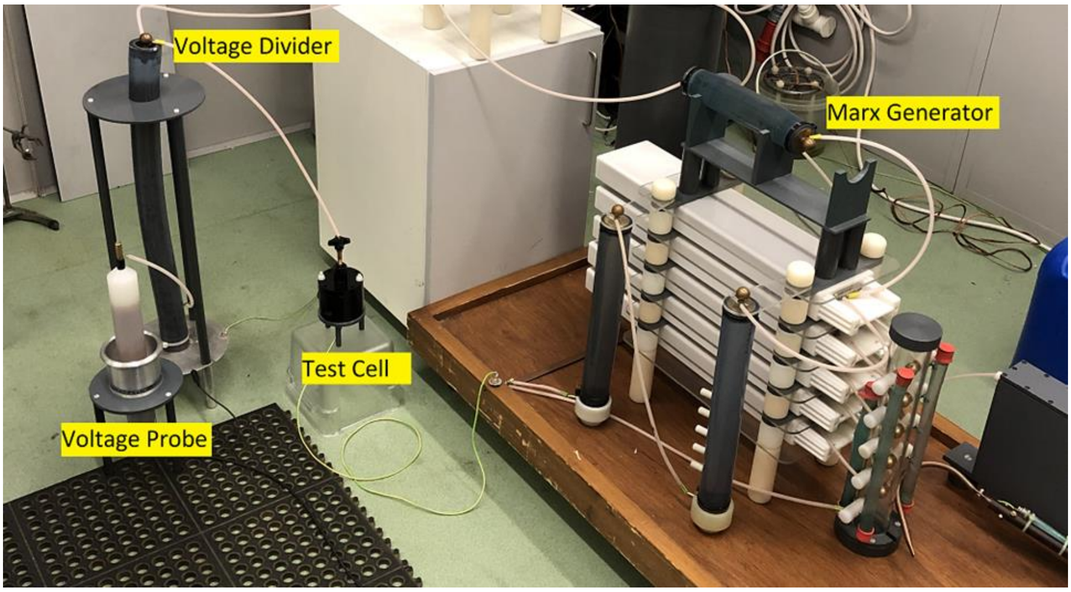


Figure 3-8; *Experimental setup used in breakdown tests, including impulse generator, test cell and diagnostics system*

The experimental setup remained consistent throughout all experimental work conducted in relation to this thesis; with all components, besides the test cell used, identical for all breakdown tests. A comprehensive description of the experimental system will now be provided in the following sections.

3.4.1. Impulse generator topology

The impulse generator used throughout all breakdown tests was a five-stage air-insulated inverting Marx type pulsed power circuit connected to a 60kV high voltage DC supply (Glassman USA). Charging current provided by the DC supply was limited with the use of a series configured 1MΩ protective resistor stack consisting of one hundred 10kΩ wire wound ceramic-case resistors (Meggitt UK) connected between voltage source and Marx generator. This type of impulse generator was used due to its versatility and ease in which output impulse may be modified, achieved by altering the R_{Front} and R_{Tail} parameters of the circuit. A general overview of the circuit topology is given in Figure 3-9.

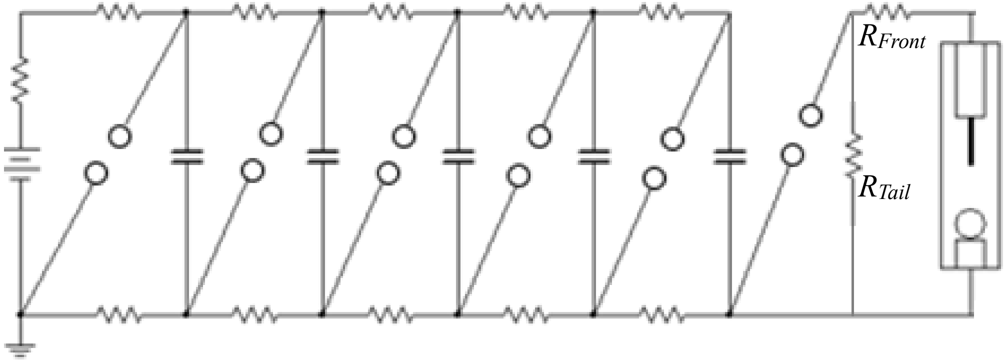


Figure 3-9; *Schematic of impulse generator highlighting wave-front and wave-tail resistors*

The energy storage elements of the pulsed power circuit are five S-Series 300nF single-ended castor oil-filled low inductance capacitors (General Atomic) producing an erected capacitance of 60nF. In order to control the charging current an inter-stage resistance of 60kΩ was provided through the use of an aqueous tube resistor filled will copper-sulphate. The terminals of each spark switch, 25mm bronze-phosphor spheres, were spaced equidistant along the length of the $CuSO_4$ resistor to ensure equal charging resistance was provided to each stage to facilitate balanced charging. Discharge resistors (2kΩ) of similar construction were connected between alternate stages to limit the flow of current between stages during discharge of the Marx.

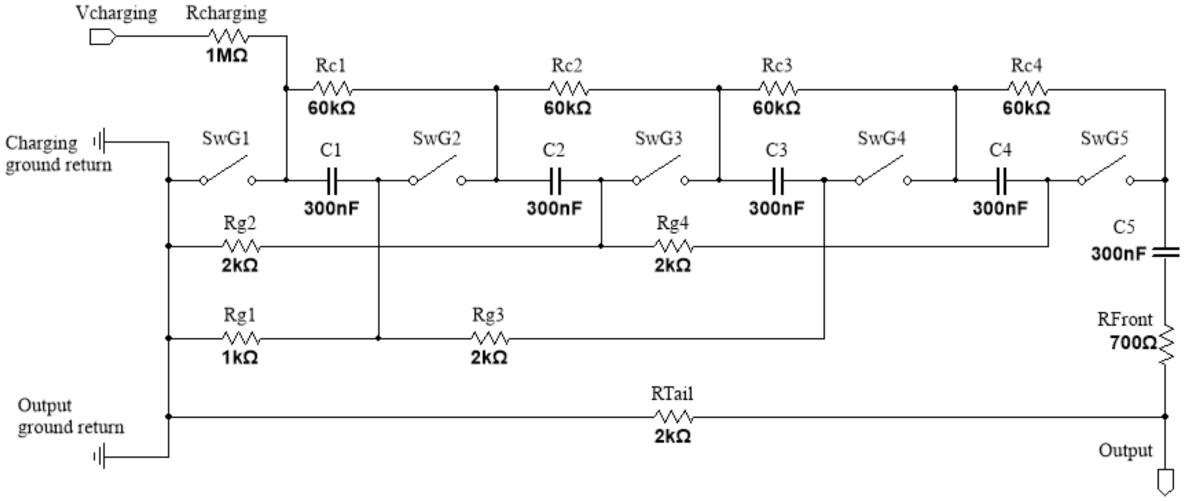
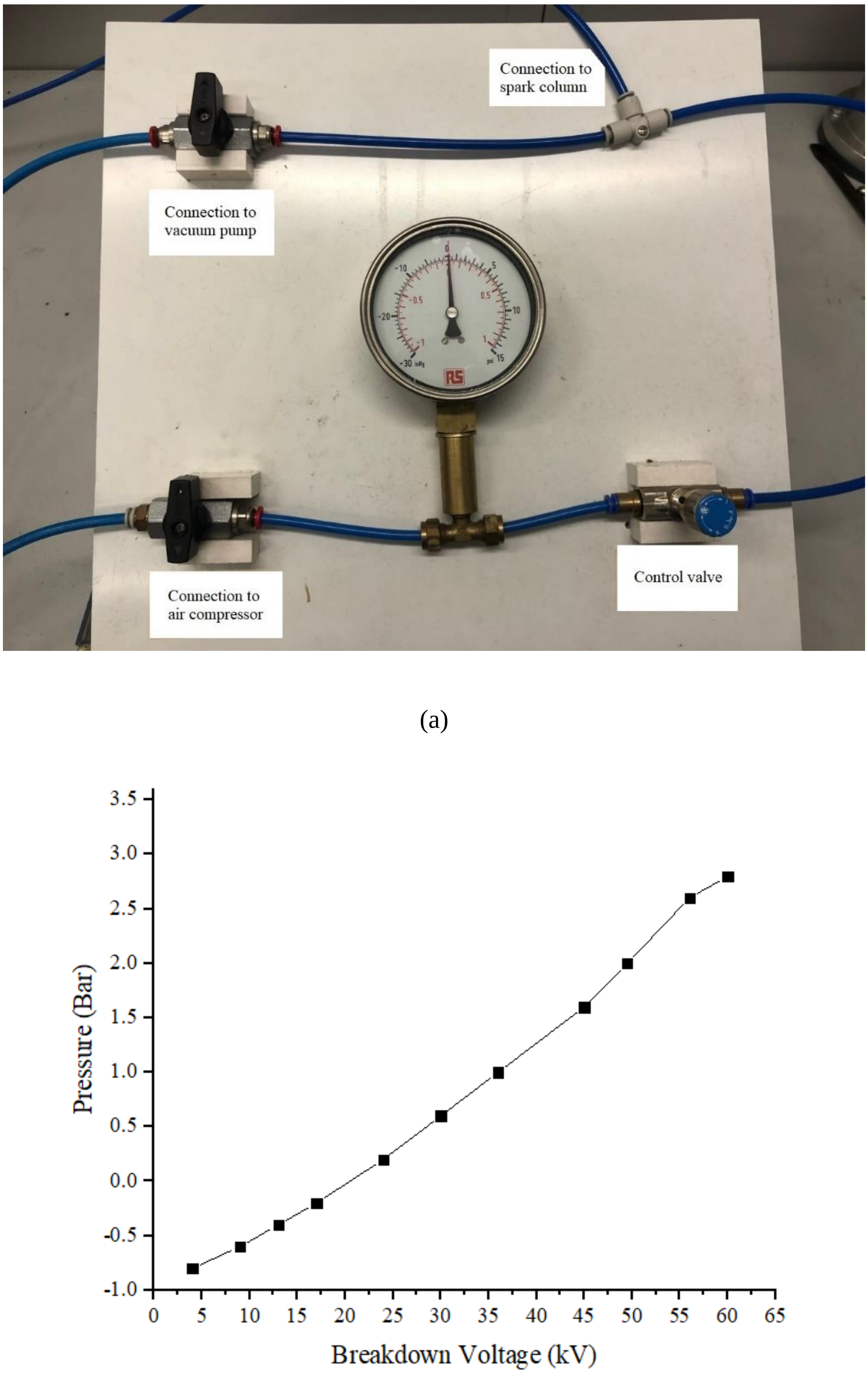


Figure 3-10; *Schematic of Marx generator circuit configured to output standard lightning impulse.*

The pulsed power circuit operates under a principle of capacitive voltage addition where all capacitors are charged to a voltage equal to that of the DC supply. When triggering of the Marx is initiated the initial voltage of V appears across the first spark switch (SwG1) which results in breakdown of the inter-electrode gap between the spherical electrodes of SwG1. This results in the grounding of capacitor C1 through as short-circuit, causing polarity inversion and as one side of SwG2 is tied to C1 the other becomes charged to -V causing a potential of 2V to appear across the gap of SwG2 where breakdown occurs almost instantaneously. This process continues until the potential across SwG5 is 5V, at which point all capacitors are series connected and voltage at the output terminals of the Marx is five times that of the charging voltage. Due to its inverting nature the output impulse will always be of opposing polarity to the energisation voltage.

Triggering of the Marx generator is achieved through a pneumatic triggering process. Prior to the charging of the generator the spark column which houses each of the spark switches is filled with compressed air using a Fiac 1.46kW air compressor, controlled through a gas control system (Figure 3-11a). This gas control system consists of three tubing junctions connecting the air compressor and vacuum pump to the spark column of the Marx generator. Pressure within the column was continually monitored with use of a commercially available pressure gauge. Once the impulse generator capacitors are fully charged air pressure within the spark column is reduced with the use of a vacuum pump. At the point of triggering of the first spark gap pressure was again increased to 1 bar to mitigate any unwanted firing of the Marx generator.



(a)

(b)

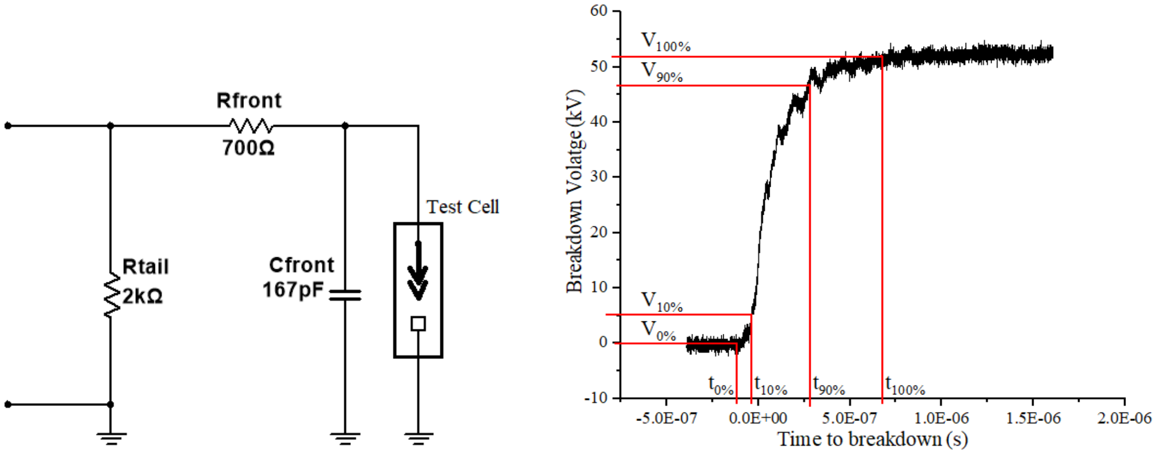
Figure 3-11; *Depiction of (a) Gas control system and (b) self-breakdown voltage of the Marx generator spark column (graph adapted from [130]).*

Breakdown of the air gap within the spark column is governed by the self-breakdown voltage of the compressed air at the specific inter-electrode gap distance. This relationship has been shown in Figure 3-11b, which depicts the self-breakdown voltage of air at a given pressure. From the data provided in

Figure 3-11b it can be seen that for the specific charging voltage used during testing (30kV) air pressure in the spark column must be maintained above 0.6 bar to avoid breakdown of the first spark gap and unwanted triggering of the Marx.

3.4.1.1. Modification of impulse wave-shapes

As the main focus of the breakdown experimentation conducted in this thesis is to evaluate the dielectric performance of liquid, and liquid-solid composite, samples under conditions representative of the voltage stress experienced in pulsed power machines a number of discrete voltage impulses had to be generated by the Marx pulsed power circuit. To achieve this the RLC parameters of the circuit had to be modified. The shortest of these impulses was of 0.4μs rise-time, the impulse circuit parameters used to achieve such a rise-time are shown in Figure 3-12a. In order to produce such a rise-time for the output waveform a CuSO4 wave front resistor of 700Ω was connected to the output terminals of the Marx generator. This resistor alone however was not enough to adequately control the rise-time of the impulse. Additional capacitance was required to slow the rise of the output impulse to achieve the desired 0.4μs rise-time; this was done be introducing six series connected 1nF capacitors (167pF total capacitance) in parallel with the breakdown test cell. The waveform produced by this particular impulse circuit topology can be seen in Figure 3-12b.

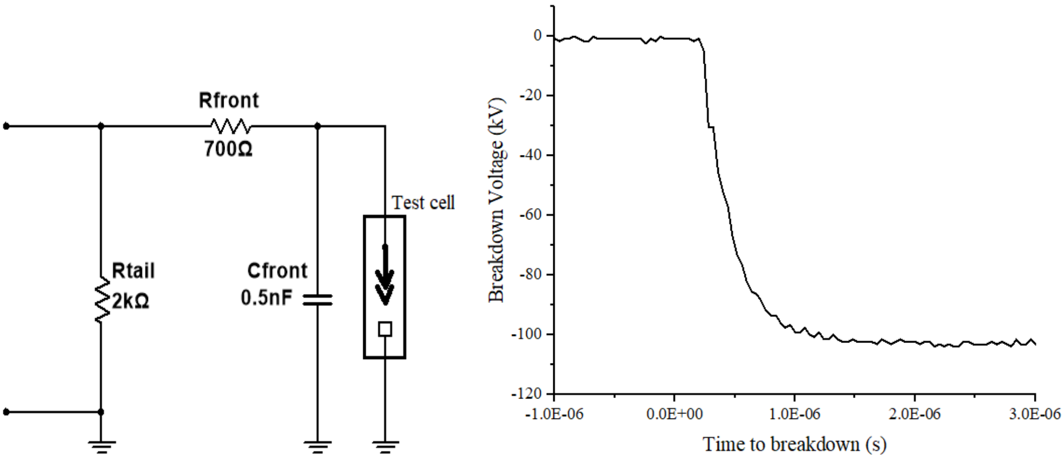


(a) (b)

Figure 3-12; (a) Schematic of the output circuit implemented to produce impulses of 0.4μs rise-time and (b) generated impulse. Example impulse is of positive polarity; however, the same output circuit was used to produce both positive and negative impulses.

Figure 3-12b also provides an overview of how the nominal rise-time of the impulse was determined. As is typical for the determination of this parameter, nominal rise-time of the impulse was taken as the time for the voltage magnitude to increase from $V_{10\%}$ to $V_{90\%}$ with a multiplication factor of 1.25 applied [131]; this methodology was also used to determine the rise-time of all impulses used during breakdown experimentation.

The next impulse waveform used during testing was the standard lightning impulse (1.2/50μs). To produce such a waveform, the same Marx setup was used as that of the 0.4μs waveform with the wave-front resistance of 700Ω maintained. Though as the rise-time of the impulse needed to be increased the capacitance connected to the output of the impulse generator had to be altered. To achieve the standard lightning impulse rise-time of 1.2μs two 1nF capacitors were connected in series and placed in parallel with the breakdown test cell; shown in Figure 3-13a.

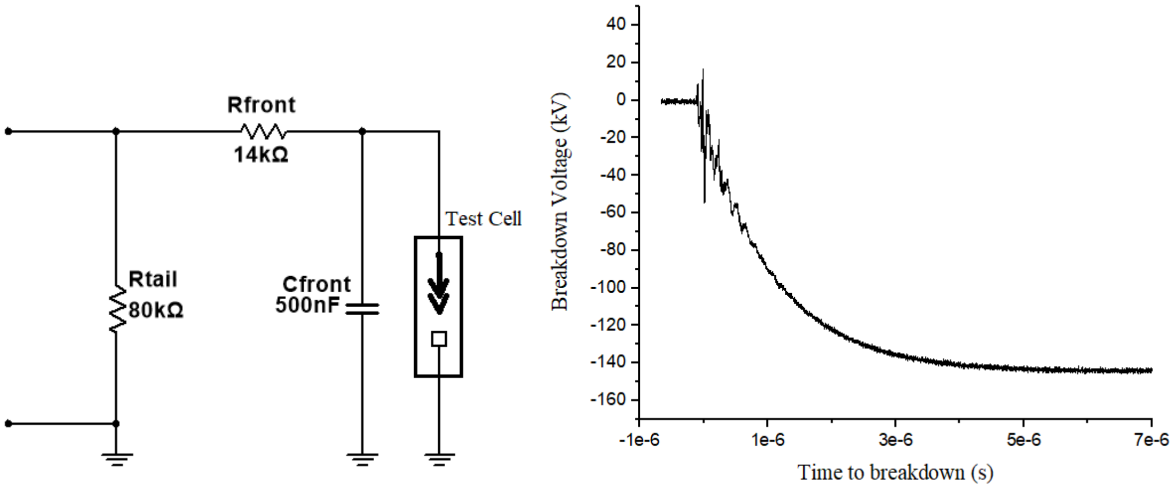


(a) (b)

Figure 3-13; *(a) Schematic of the output circuit implemented to produce impulses of 1.2μs rise-time and (b) generated impulse. Example impulse is of negative polarity; however, the same output circuit was used to produce both positive and negative impulses.*

As can be seen from the waveform in Figure 3-13b, the chosen RLC parameters of the circuit in Figure 3-13a were adequate to produce the desired 1.2μs rise-time. As with the 0.4μs impulse, this rise-time was defined as the time taken for voltage magnitude to increase from 10% to 90% of the peak value, with the fall time taken at the time for voltage magnitude to reduce from the peak value to 50% of this value. The required fall-time of 50μs was achieved with the use of a 2kΩ wave-tail resistor; it must be said though that due to all breakdown events taking place on the rising edge of the impulse the wave-tail was of negligible importance in the work conducted in this thesis.

The final waveform used during the bulk and interfacial breakdown experimentation was one of 7μs rise-time. As the rise-time of this waveform was considerably longer than the two other waveforms (0.4μs and 1.2μs), both the resistance and capacitance of the Marx circuit had to be modified. To achieve such a slow rise-time the wave-front resistance had to significantly increased to a value of 14kΩ, while wave-front capacitance was set to the same 0.5nF used during the tests conducted with the 1.2μs impulse; again achieved with the use of two series connected 1nF capacitors.



(a) (b)

Figure 3-14; *(a) Schematic of the output circuit implemented to produce impulses of 7μs rise-time and (b) generated impulse. Example impulse is of negative polarity; however, the same output circuit was used to produce both positive and negative impulses.*

As can be seen in Figure 3-14b the final waveform has a much slower rise to peak magnitude that the other two previously presented waveforms. Rise-time of this waveform was shown to be as desired (7μs); determined by using the same aforementioned methodology of taking the time from $V_{10\%}$ to $V_{90\%}$ and applying a multiplication factor of 1.25.

3.4.2. Design of test cells used in experimental work

During the experimental studies presented in this thesis two discrete test cell designs were used. Each of these bespoke test cells was associated with a particular type of breakdown test. The following sections will describe each of these test vessels in detail.

3.4.2.1. Test cell for bulk breakdown experimentation

The vessel used throughout all bulk liquid breakdown testing was constructed from glass reinforced Nylon and has an inner diameter of 55mm and a total volume of ~150ml (Figure 3-15). This is comparable to test cell designs used in other research studies in the field [18], [132], [133]. During all bulk liquid breakdown experimentation, a highly divergent electric field was maintained in order to ascertain the effect impulse polarity may have on the dielectric strength of the chosen fluids. Consequently, a needle-sphere electrode geometry was selected for use throughout all breakdown tests.

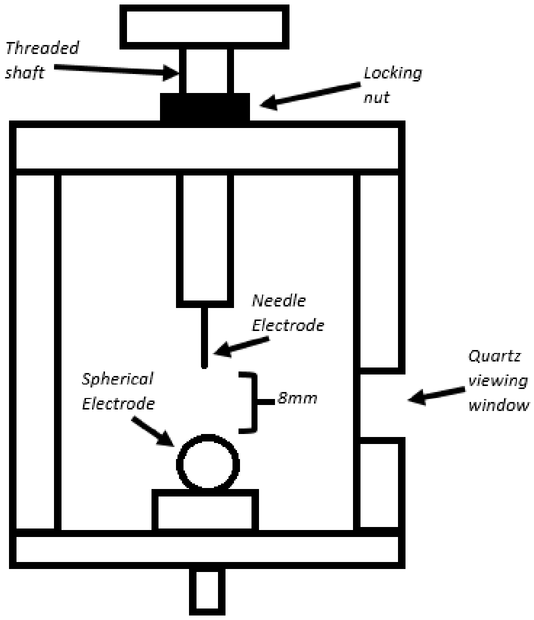


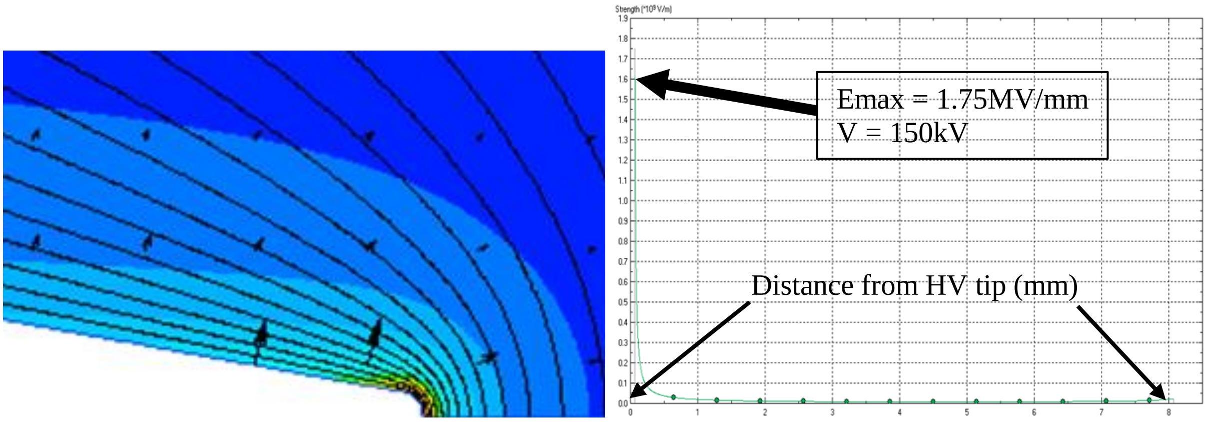
Figure 3-15; *Schematic of test cell used in bulk liquid breakdown tests.*

The high voltage electrode, in this case a gramophone needle of ~35µm tip radius, was held in place using a locking system which consists of a cross-cut pin and Nylon tightening cap. Gramophone needles provide consistency in the tip radius of the HV electrode, and thus the developed electric field. They are also recommended to be used as high voltage electrodes in liquid insulation breakdown tests by

ASTM International Standard [83]. When the needle is placed inside the pin it is fixed in place by screwing the cap over the pin, this ensures that the needle is held in place and that no discharge will be produced from the threading on the needle holder. The ground electrode, a mild steel ball bearing of ½ inch diameter, obtained from Rapid Electronics, is fixed in place using a simple magnetic holder. This provides a firm adhesion for the electrode as well as allowing ease of electrode replacement post-testing.

Even though the inter-electrode gap was fixed at 8mm throughout all bulk liquid breakdown tests a means of facilitating movement of the HV electrode had to be developed in order to fix the gap before conducting breakdown tests. This was done by reducing the inter-electrode gap to 0mm; i.e. direct contact between HV needle and grounded sphere then increasing the gap until the desired 8mm spacing had been achieved. The chosen method was to mount the needle holder onto a threaded shaft. This allowed the gap to be altered simply by turning a handle on the top of the test cell. Once the chosen gap size has been achieved the shaft was then fixed in place with the use of a locking nut.

In order to determine the degree of field non-uniformity, or the field utilisation factor, an electrostatic field analysis was performed using Finite Element Modelling (FEM) package QuickField from Tera Analysis. This procedure allowed for the determination of the maximum field magnitude of electric field developed in the vicinity of the HV needle electrode which was then compared to the average field across the inter-electrode gap distance; as described in Section 2.4.3.



(a) (b)

Figure 3-16; *(a) FEM model of electric field distribution within the bulk liquid breakdown test cell and (b) field magnitude across inter-electrode gap as predicted by FEM package.*

This form of field analysis evaluates the Laplacain field distribution within the system and thus does not account for any space charge which may be developed as a precursor to breakdown. It does however provide an accurate estimation of the maximum electric field developed at the sharpest point of the HV needle and therefore provides adequate information to derive the field utilisation factor. Throughout all bulk liquid breakdown tests a field utilisation factor of η ~0.01 was maintained.

3.4.2.2. Test cell used during interfacial breakdown study

The test cell used for all interfacial flashover tests consisted of a PVC body formed of four cylindrical legs and Perspex outer walls held in place with a disc shape top and base. Acrylic Perspex was chosen for the outer walls of the test cell as this would allow for reduced complexity in optical monitoring of interfacial flashover upon breakdown. The test cell is of ~500ml volume, although to ensure breathability only 250ml of the investigated dielectric fluid was used for a given sample. This air gap also encourages any microbubbles present post-degassing, or post-breakdown, to travel upwards and reduce any possible influence exerted on breakdown dynamics.

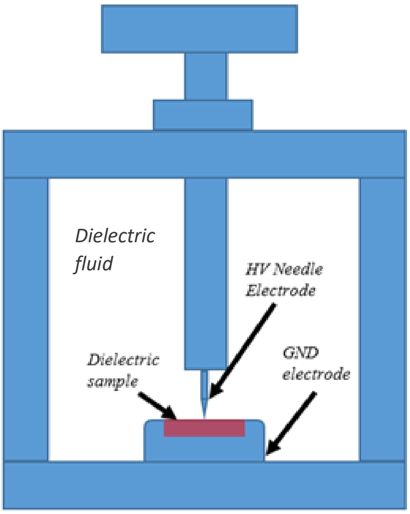
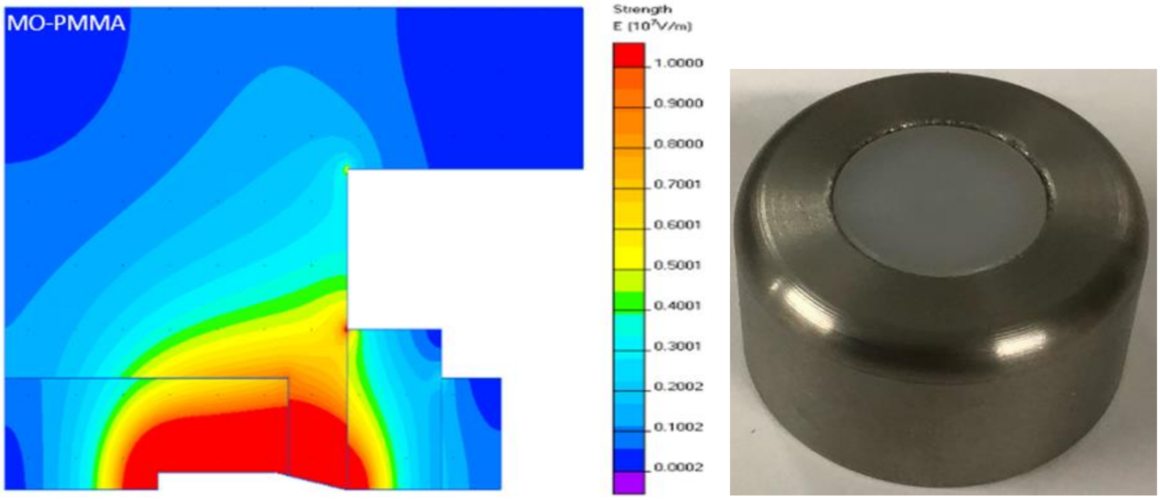


Figure 3-17; *Schematic of test cell used in interfacial flashover study.*

The breakdown tests were conducted in a needle-plane electrode configuration. A gramophone needle with a nominal tip radius of ~35µm was used as the HV electrode, with a 40mm diameter mild steel ground electrode. Comprehensive analysis of the electric field distribution within the test cell resulted in the use of a recess, ‘ring’, design for the grounded electrode. Similar to the test cell used in bulk breakdown experimentation the HV electrode is fixed onto a screwed rod and covered with a Nylon cap. This allows for the adjustment of the HV electrode to ensure a true contact with the polymer dielectric sample which will mitigate any possible field enhancement which may occur if a liquid gap exists between the tip of the HV needle and the solid polymer sample; as described in Section 2.7.2.



(a) (b)

Figure 3-18; *(a) FEM model of electric field magnitude and distribution within the interfacial flashover test cell and (b) 'ring' style ground electrode used in flashover study.*

Field distribution can be seen to favour interfacial (liquid-solid) flashover with the use of the ring design of ground electrode. Utilisation of the ring design has also resulted in a favourable propagation path to ground for any developed streamer(s) across the liquid-solid interface. Analysis of the electric field distribution in the system showed that the greatest field magnitude (2.78MV/mm) occurred at the point of contact between the HV needle and solid polymer interface; this is to be expected given the triple point effect; described in Section 2.7.2.

3.5. Diagnostics system

To facilitate the recording of breakdown voltage measurements a combination of resistive and electronic diagnostic devices were used throughout all experimental work. This system consisted of a voltage divider column, high voltage probe and digital oscilloscope. The interconnection of these devices, as well as their connection to the impulse circuit, can be seen in figure 3-19.

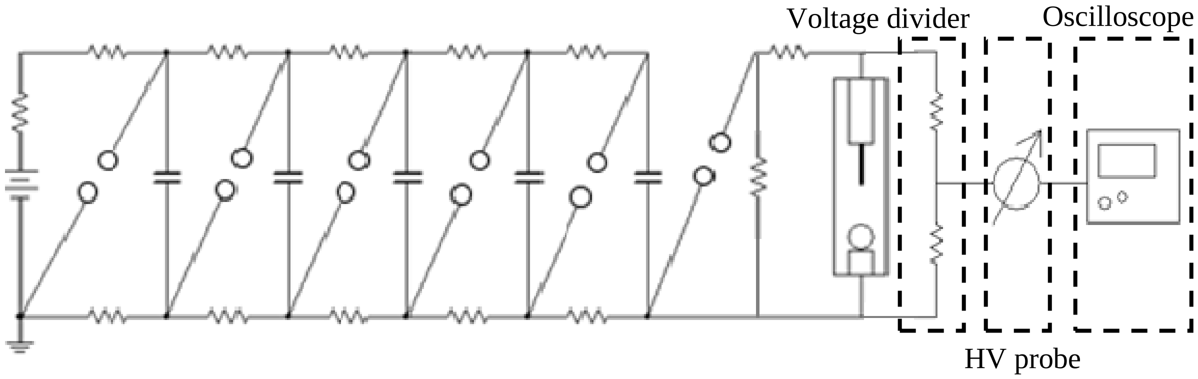


Figure 3-19; *Schematic of experimental setup, highlighting the diagnostics system.*

In order to allow adequate measurement of breakdown voltage impulses a HV divider was connected in parallel with the test cell. This custom-built two-stage divider, a $CuSO_4$ water solution filled column, was constructed from a 50mm diameter PVC tube. The high voltage electrode of the divider was a 25mm bronze-phosphor sphere which resides inside the aqueous $CuSO_4$ solution with a short length of M6 screwed rod utilised to maintain connection between the electrode and external circuit. To ensure appropriate mitigation of field enhancement around this rod a 20mm bronze-phosphor sphere was connected to the portion of the rod which exits the top of the divider. The tapping point, to which the HV probe was connected was formed of a 10mm bronze-phosphor electrode placed within the $CuSO_4$ connected via a short length of M3 screwed rod to a similarly sized bronze-phosphor electrode on the external body of the PVC tube. Earthing of the divider was achieved with the use of a 40mm length of 50mm diameter brass rod fixed to a 250mm diameter aluminium plate of 3mm thickness.

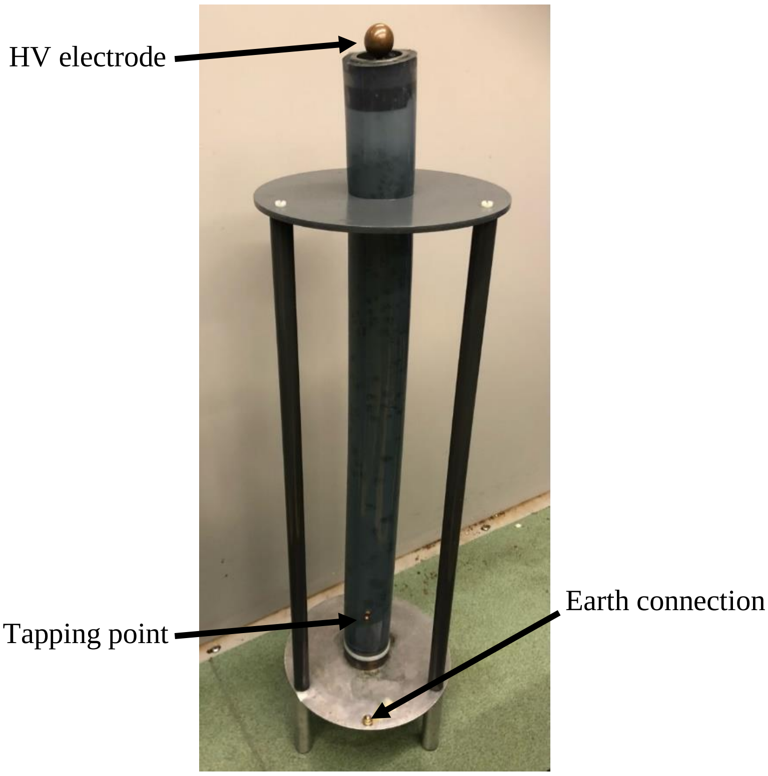


Figure 3-20; *$CuSO_4$ HV divider used in all breakdown experiments.*

The division ratio of the divider is generated due to the difference in the length of the path to ground of the HV electrode and tapping point. As the HV electrode resides at the top of the divider the distance to ground is 700mm while the tapping point is placed at one-tenth of this distance (70mm) from the ground connection. Such a configuration produces a ratio of 1:10 on the output tapping point; i.e. a voltage of 150kV applied to the HV electrode would result in a voltage of 15kV appearing at the output of the divider. This division ratio was re-evaluated before each series of breakdown tests to ensure no changes had occurred.

The magnitude of voltage impulses was further reduced by the inclusion of a NorthStar PVM5 HV probe connected to the tapping point of the HV divider and ground. The HV probe provides a division ratio of 1000:1, resulting in a total division ratio of 10000:1 for the entire diagnostics system. The NorthStar probe is rated to 60kVDC or 100kV impulse, meaning theoretically the maximum measurable voltage to avoid system saturation is 600kVDC or 1MV impulse at the HV electrode of the divider; this is way in excess of what was expected during the breakdown experimentation. Nominal bandwidth of the NorthStar PVM 5 HV probe is 80MHz.

All experimental voltage signals were captured and recorded using a Tektronix TDS3054C digitising oscilloscope of nominal bandwidth 500MHz and a sampling rate of 5Gs/s. Such a device is more than adequate to record all breakdown impulses given the waveforms used during experimental works; described in detail in Section 3.4.1.1.

3.6. Breakdown testing methodology

In order to facilitate comparability of results generated during the experimental work detailed in this thesis a comprehensive testing methodology was applied for all breakdown tests. A specific methodology was developed for each of the discrete breakdown studies conducted; bulk liquid breakdown and liquid-solid interfacial flashover. Each of these methodologies will be described in detail in the proceeding sections.

3.6.1. Experimental methodology for bulk liquid breakdown tests

To increase understanding of the breakdown parameters exhibited by different insulating liquids in pulsed power regimes, the work conducted in this thesis diverged from the commonly used standard testing methods of IEC60897 and ASTM D3300. Voltage impulses (as described in Section 3.4.1.1) of both positive and negative polarity were applied in an overstressed regime. This ensures that each breakdown event occurs on the rising slope of the HV impulse and thus provides a direct link between breakdown voltage and time delay to breakdown. A nominal DC charging voltage of 30kV was used throughout all bulk liquid breakdown tests; allowing for a peak nominal output of 150kV from the Marx pulsed power circuit. This nominal output voltage was selected to guarantee that all breakdown events took place on the rising slope of the energising impulse (or at the peak of the applied voltage impulse), thus ensuring that all breakdowns are controlled by the initiation processes rather than the propagation voltage as defined in [71].

To mitigate any influence contaminants may have on the observed breakdown performance of the liquid dielectrics both the test cell and electrodes were cleaned with ethanol solution prior to the conduction of any breakdown tests. Once cleaned and allowed to air dry, the new electrodes were fixed within their respective holders inside the test cell and the vessel was filled with the liquid of interest. At this point the test cell was placed under vacuum for 30mins to remove any gas bubbles before a sequence of breakdown tests were performed. Each new liquid sample was exposed to ten breakdown events (waiting time between successive shots set at five minutes) with the breakdown voltage and time to breakdown associated with each of these ten breakdown events recorded. After the ten registered breakdown events both the HV needle and ground spherical electrodes were replaced and a fresh liquid sample was introduced into the test cell. In total, 3 new samples of each liquid in each RH state were examined. This data was then subjected to mean value analysis, with 95% confidence intervals applied to determine the statistical similarity of the three individual liquid samples (as described in Section 3.7.2). Once statistical similarity of the data was confirmed it was grouped to form a larger dataset of n = 30 individual breakdown events for a given liquid and state of relative humidity, which was then used for cumulative probability analysis. The average values of the breakdown voltage and time to breakdown were calculated using these 30 breakdown event datasets, 95% upper and lower confidence intervals were obtained for each average value using the Student coefficients for (N-1) degree of freedom. This methodology was implemented in all bulk breakdown experimentation, with the findings of this work discussed in Chapter 4, 5 and 6 of this thesis.

3.6.2. Experimental methodology for liquid-solid interfacial flashover tests

Five individual 8mm thick samples of each solid material were immersed in the chosen dielectric fluids, and stressed with the same HV impulse voltages used throughout the bulk liquid experimentation (0.4µs, 1.2µs and 7µs) until the occurrence of interfacial breakdown, or breakdown through the bulk of the solid dielectric. Again, an overstressed voltage was applied to the samples to ensure correlation between breakdown parameters. For the interfacial flashover tests the nominal DC charging voltage was set at 25kV which produced a nominal peak output of 125kV on the output of the pulsed power circuit.

To negate any possible influence of surface defects or asperities all solid polymer samples were polished, as described in Section 3.3.2, and cleaned with ethanol solution prior to being tested; as were the HV and ground electrodes and allowed to air dry. Once the electrodes and solid samples were suitably dried they were placed within the breakdown test cell and immersed in the liquid under test. The test cell was then placed within a vacuum chamber for 30mins to ensure the removal of all vapour bubbles present in the dielectric fluid.

For each liquid-polymer sample breakdown parameters (breakdown voltage and time to breakdown) were logged for ten individual interfacial flashovers, or a single bulk breakdown of the polymer dielectric. Applying such a methodology allowed for determination of both the level of voltage required to cause complete breakdown of the composite insulation system, as well as providing an indication of the likelihood of the different types of breakdown occurring. Once a given breakdown test had been completed the test cell was emptied and the polymer sample was removed from the ground electrode. Before the next series of tests, a fresh solid sample, liquid sample and new HV needle were placed within the test cell, with the same ground electrode used throughout test; as aforementioned, all elements were cleaned and allowed to air dry prior to any tests being conducted.

3.7. Analytical methodology

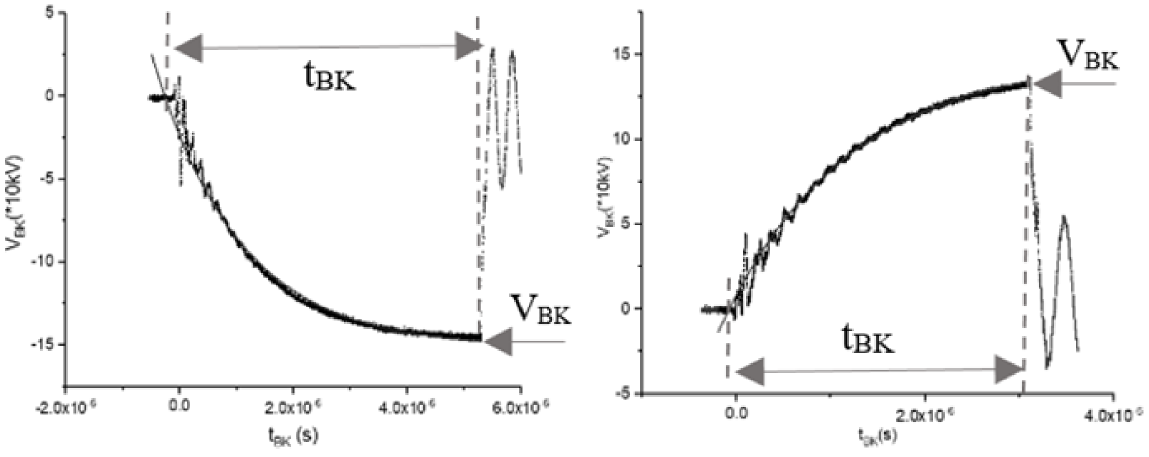
Once experimental data had been obtained, a suitable analytical methodology had to be implemented to allow for comparability between all obtained results; not only cross-experiment but also with those detailed in already published research work.

3.7.1. Treatment of experimental breakdown data

A standardised method was derived for obtaining the desired breakdown parameters from experimental data. Furthermore, this also assisted in the mitigation of possible ambiguity in the magnitude of voltage at the point of breakdown; due to the presence of distortions in the recorded signals resulting from parasitic inductance and capacitance inherent within the experimental system.

$$V_{Breakdown} = V_0 \, exp\left(-\frac{t}{t_0}\right) + V_{offset} \qquad (3.1)$$

During this procedure pre-breakdown parts of all experimental waveforms were fit with an exponential growth function (equation 3.1); achieved using Origin Pro graphing software (goodness of fit coefficient R2 ~0.98-1). Examples of such a fit for positive and negative waveforms are shown in Figure 3-21.



(a) (b)

Figure 3-21; *Exponential fitting process applied to both (a) negative and (b) positive waveforms; implemented in Origin Pro. Dark lines, experimental waveforms; grey lines, analytical lines (3.1) fitted in Origin Pro graphing software.*

Breakdown voltage was obtained from the point on the fitted curve at which the collapse of the voltage signal occurs. The time to breakdown was taken from the zero-crossing point of the exponential fit curve to the point when the voltage is observed to collapse. Once the breakdown parameters were gathered a number of statistical analysis techniques were applied to the obtained datasets; including mean value analysis and cumulative probability function under normal distribution.

3.7.2. Confidence interval analysis

For the post-experimental analysis of the bulk liquid breakdown data the decision was taken to calculate the mean values of breakdown voltage and associated times to breakdown for each of the three dielectric liquids and 95% confidence intervals for these mean values. The mean values of breakdown voltages and times to breakdown have been obtained assuming the normal distribution of these values, i.e. $\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$, where X is the measured quantity and N is the number of measurements. The 95% confidence intervals have been obtained using the graphing software package OriginPro. Confidence intervals can be used to assess the accuracy of the estimated mean values. Also, if specific significance level is defined (typically $\alpha = 0.05$), it can be stated that two mean values are statistically different at this level of significance if their confidence intervals do not overlap (i.e. the confidence intervals do not contain corresponding null hypothesis values). For example, the authors [134] show that if 95% confidence intervals for a pair of mean values obtained using independent samples do not overlap, the corresponding *p*-value (i.e. the probability of wrongly rejecting a null hypothesis) is less than $\alpha = 0.05$. However, if the 95% confidence intervals for two means values (obtained from independent samples) overlap, further analysis is required to make a conclusion on the *p*-values, [134].

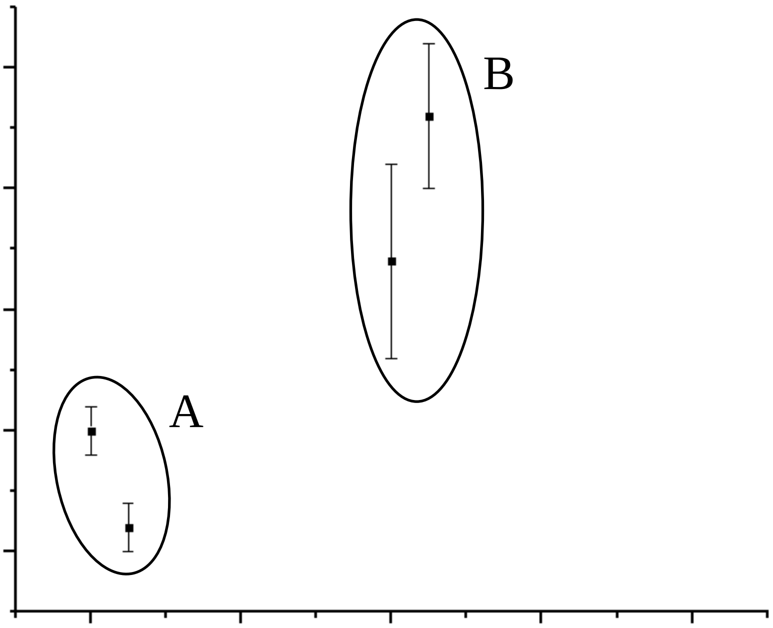


Figure 3-22; *The application of confidence intervals to mean value data points showing (a) statistical difference in the data and (b) the likely absence of statistical difference in the data.*

Case A in Figure 3-22 shows non-overlapping error bars which represent the confidence intervals, and thus it may be stated that the sample means are different from each other at specific level of significance. However when the confidence intervals overlap, as shown in Case B in Figure 3-22, the resultant *p*-value depends on degree of overlapping [134], and thus a conclusion on the difference between two means at the specific level of confidence cannot be reached based solely on visual analysis. Similar conclusions to those in [134] were also made in [135] and [136].

Chapter 4 – Lightning impulse breakdown of insulating fluids

4.1. Introduction

The proceeding chapter is concerned with the presentation and discussion of experimental results obtained from breakdown tests conducted under standard lightning impulse stress. The impulsive breakdown characteristics of the chosen liquids were obtained in accordance with the testing methodology described in Section 3.6.1. Within this chapter the breakdown voltage and time to breakdown for each of the liquids tested in this work have been obtained based on ten individual breakdowns of a single liquid sample, the mean of these values and 95% confidence intervals are presented along with the cumulative probability function for the entire dataset obtained for a given dielectric liquid. Firstly, experimental data will be presented and evaluated for similarity between the breakdown of individual liquid samples of a given dielectric fluid and relative humidity. Analysis of the mechanisms that may be responsible for the behaviours observed will be presented and discussed within the summary (Section 4.3) at the end of the chapter.

4.2. Experimental results

This section, and associated subsections, detail the results gathered for breakdown of the liquid samples under lightning impulse stress. The obtained experimental data has been subdivided into groupings based on the three discrete levels of relative humidity of each liquid sample. These were 'As received' (RH between 9% - 21%), 'Ambient humidity' (RH ~35%) and 'Elevated humidity' (RH >70%); discussed in detail in Section 3.3.1.

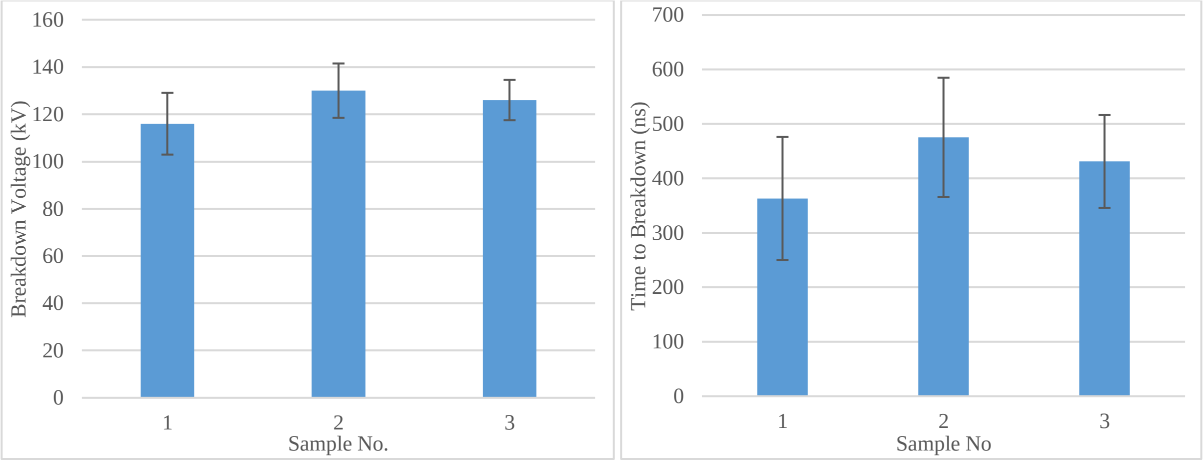
4.2.1. Breakdown of liquid in 'As Received' condition

Data presented in this section pertains to the breakdown of liquid samples in the condition as provided by the manufacturer; i.e. the liquid samples are taken from sealed containers provided by the manufacturer. The only conditioning of the liquid samples was that of degassing prior to the commencement of any breakdown tests; as discussing in Section 3.6.1. The relative humidity of liquid samples in the ‘As Received’ condition was 21%, 12.5% and 9% for the mineral oil, synthetic ester and natural ester, respectively.

4.2.1.1. Breakdown of mineral oil in the ‘As Received’ condition

The first set of breakdown results presented are those gathered for the mineral oil Shell Diala S4. This data can be thought of as providing a benchmark for the performance of conventional insulating liquids commonly found within large electrical machines and pulsed power apparatus and thus sets a precedent to which the performance of the ester-based fluids can be evaluated against.

When examining the measured breakdown voltage and time to breakdown for each of the samples of mineral oil it was evident that no clear upward or downward trend (change in the breakdown voltage and time to breakdown with breakdown number) exists for any of the three liquid samples tested under either energisation polarity. Based on the absence of any visible upward or downward trend in breakdown voltage, or time to breakdown, it is reasonable to pool these datasets to allow for a much greater sample size; i.e. n = 10 to perform mean value analysis.



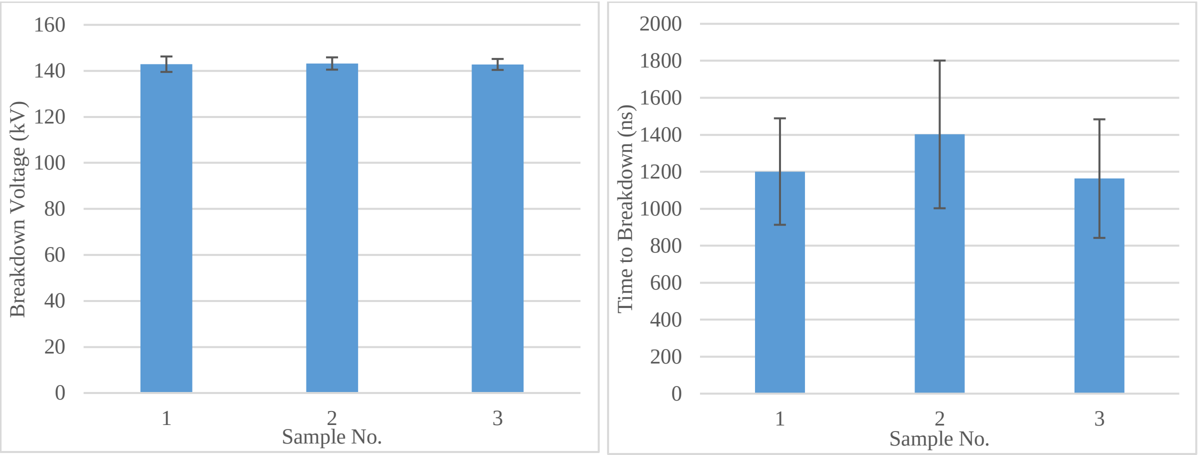
(a)

(b)

Figure 4-1; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When evaluating the average breakdown voltage values for each liquid sample when under positive voltage impulse (Figure 4-1a) statistically significant difference, at the degree of confidence discussed in Section 3.7.2, may not exist in the breakdown voltages of individual liquid samples due to significant overlapping of the confidence intervals. This absence of statistical variation in the breakdown voltages of each liquid sample supports the suitability of the data to be pooled into one large dataset.

The presented average time to breakdown data (Figure 4-1b) shows identical behaviour to the breakdown voltage data, with statistically significant variation at the selected degree of confidence unlikely seen between samples. However, the spread of the time to breakdown data, shown in the error bars (95% confidence intervals), is larger than the spread in the breakdown voltage data. This can be attributed to breakdown of some shots being outliers from the rest of the dataset. These breakdown shots would have occurred at a point where time varied much more than voltage; such as close to the peak of the nominal voltage impulse.



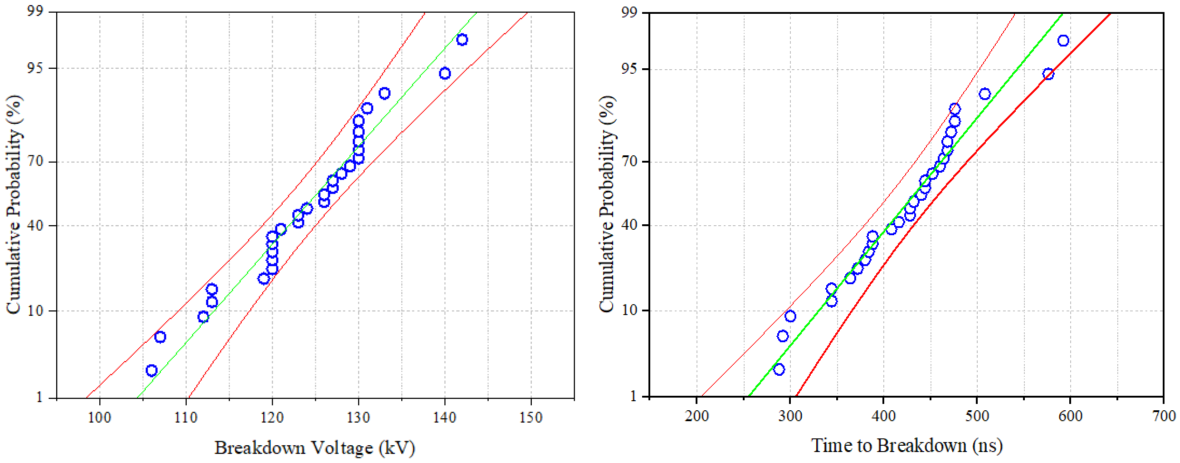
(a) (b)

Figure 4-2; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When stressed with negative lightning impulse again a statistically significant difference at the selected degree of confidence may not be observed in the average breakdown voltage values of each liquid sample. There is almost no variance in the average values of breakdown voltage for each of the tested mineral oil samples; with only a 1% difference seen in the highest and lowest values of average breakdown voltage. This is due to breakdown under this negative impulse occurring close to the peak nominal output of the impulse circuit (150kV). Thus, time to breakdown in this case is a more indicative parameter of dielectric performance than breakdown voltage

When evaluating the average values of time to breakdown for the liquid samples under negative lightning impulse (Figure 4-2b) it is apparent that breakdown took place on, or near, the plateau of the voltage impulse. This can be seen in the values of time to breakdown for all three samples with Sample 1 and 3 possessing times almost that on the nominal rise-time of the impulse (1200ns); 1201ns and 1163ns respectively, and the average value for time to breakdown for Sample 2, which was calculated to be 1402ns. Like the average values of negative breakdown voltage, a statistically significant variation may not be present in the calculated values of time to breakdown (at $\alpha = 0.05$) with all 95% confidence error bars seen to overlap. Again the variation of the time to breakdown data is much larger than that of the breakdown voltage data; in this case however, this is attributed to all breakdown events occurring at the peak of the voltage impulse were the change in voltage is much lower than the change in time.

The obtained experimental data on breakdown voltage and associated time to breakdown when the liquid samples were stressed with positive lightning impulse can be assumed to be distributed normally. This is confirmed as the pooled sample dataset was subjected to the Kolmogorov-Smirnov (KS) normality test and possessed p-values (goodness of fit coefficient) of 0.8 for the breakdown voltage data and 0.64 for the associated time to breakdown. This allowed for for the calculation of mean values and standard deviation of the data as well as the 1% to 99% probability of breakdown.

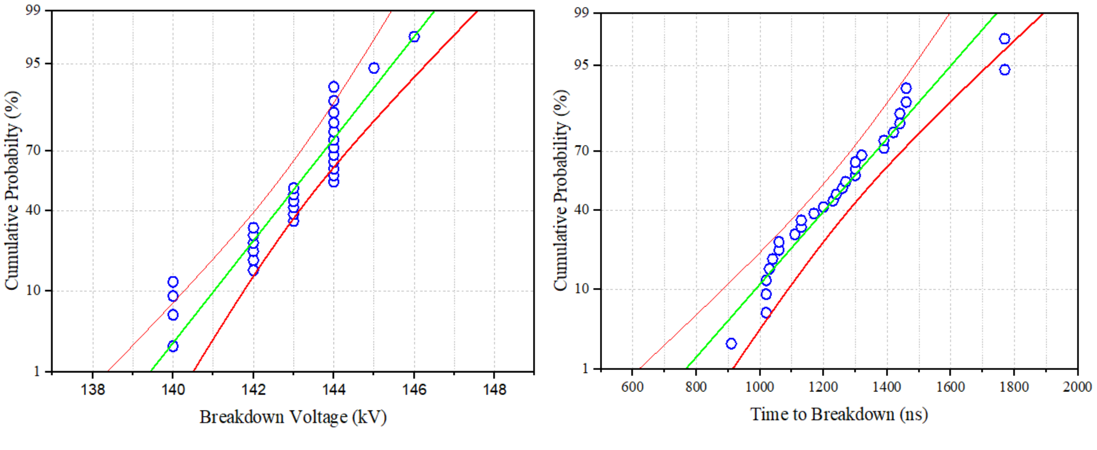


(a) (b)

Figure 4-3; *Probability plots for 'As Received' mineral oil; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

Predicted breakdown voltages for the mineral oil are $V_{10\%}$ = 113kV, $V_{50\%}$ = 124kV and $V_{95\%}$ = 138kV. These percentiles, particularly the 50th percentile, are commonly used to evaluate the safe operating voltages for large electrical machines as they correspond to a given probability of breakdown. When examining the CPF of breakdown voltage, it can be seen that some data points deviate from the normal distribution line, though all data still resides within the upper and lower 95% confidence intervals. Obtained data on breakdown voltage of the mineral oil under positive lightning impulse is however clearly in good agreement with the normal distribution within the range of the 40th to 70th percentile with data points in this range residing on the distribution line.

In the case of the time to breakdown of the mineral oil samples data agrees with the predicted distribution over a much larger percentile range than that of the breakdown voltage. As can be seen from the CPF (Figure 4-3b), the data resides on the distribution line between the 10th and 70th percentiles with data above and below these levels seen to deviate from the predicted distribution line. Though again as with the breakdown voltage data, all points are still contained within the upper and lower confidence intervals. Figure 4-3b shows that for the percentiles of interest (10th, 50th and 95th) the time to breakdown of liquid samples was 331ns, 423ns and 542ns respectively.



(a) (b)

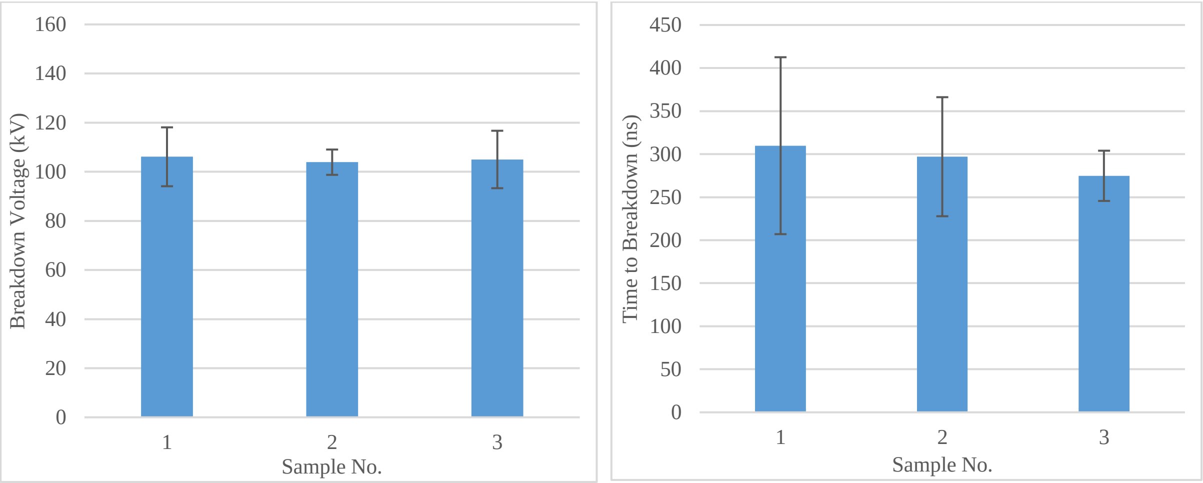
Figure 4-4; *Probability plots for 'As Received' mineral oil; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPFs of the breakdown voltage and time to breakdown of mineral oil when stressed with negative lightning impulse are presented in Figure 4-4a and 4-4b. Normal distribution of the breakdown voltage and time to breakdown data was confirmed by the KS normality test, with p-values for each parameter 0.1 and ~1 respectively. However, when examining the CPF of the breakdown voltage data it is clear that the data plot deviates from the normal distribution line at numerous points. This can be attributed to the values of breakdown voltage being contained within a small range; as aforementioned, this is because breakdown of the mineral oil samples occurred close to the nominal peak amplitude of the voltage impulse thus variation in obtained values for this parameter were minimal. Irrespective of this the breakdown voltages predicted at the percentiles of interest (10th, 50th and 95th) are 141kV, 143kV and 146kV respectively.

As is evident from Figure 4-4b a large majority of the time to breakdown data resides on the normal distribution line with data points between the 10th and 80th percentiles shown to have good agreement with the predicted normal distribution. The time to breakdown values associated with the percentiles of interest (10th, 50th and 95th) were shown to be, 986ns, 1255ns and 1600ns respectively.

4.2.1.2. Breakdown of synthetic ester in the 'As Received' condition

As described in Section 3.6.1 each liquid sample was subjected to ten breakdown events (shots) with breakdown voltage and time to breakdown logged for each event. From review of the data obtained for each individual breakdown of the synthetic ester samples it can be said that no discernible tendency exists in the breakdown voltage or time to breakdown for a given sample irrespective of impulse polarity. Under both positive and negative lightning impulse the breakdown parameters are shown to fluctuate upward and downward across the ten breakdown events performed for each liquid sample. Given the low variance and that lack of clear tendency in the breakdown voltage and time to breakdown data of the three samples it is again acceptable to pool the data recorded for each sample into a larger dataset for more accurate statistical analysis.

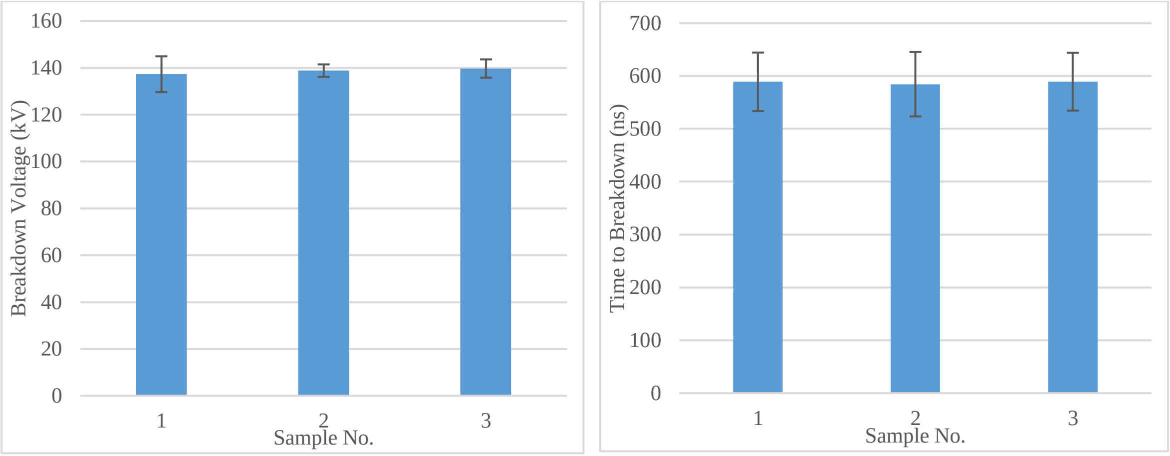


(a) (b)

Figure 4-5; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage of the three individual synthetic ester samples can be seen in Figure 4-5a. Again, statistical differences may not be present in the average breakdown voltage of the three tested samples at the selected degree of confidence; due to the overlapping of the 95% confidence error bars. It is clearly evident from the data in Figure 4-5a that breakdown of the synthetic ester samples under positive lightning impulse consistently occurred at a similar level of voltage with only a 2% difference between the highest and lowest average values.

When examining the data on the average time to breakdown of the synthetic ester samples some dissimilarities to the breakdown voltage observations exist. Namely that the shortest average time to breakdown does not correspond to the sample with the lowest breakdown voltage. This discrepancy can be attributed to outlying data points existing within the dataset of Sample 2; with this confirmed by the size of the error bars associated with this liquid sample. As with the average breakdown voltage data, any statistically significant difference in the average time to breakdown between liquid samples (at the selected degree of confidence) may not exist due to the overlapping confidence intervals.

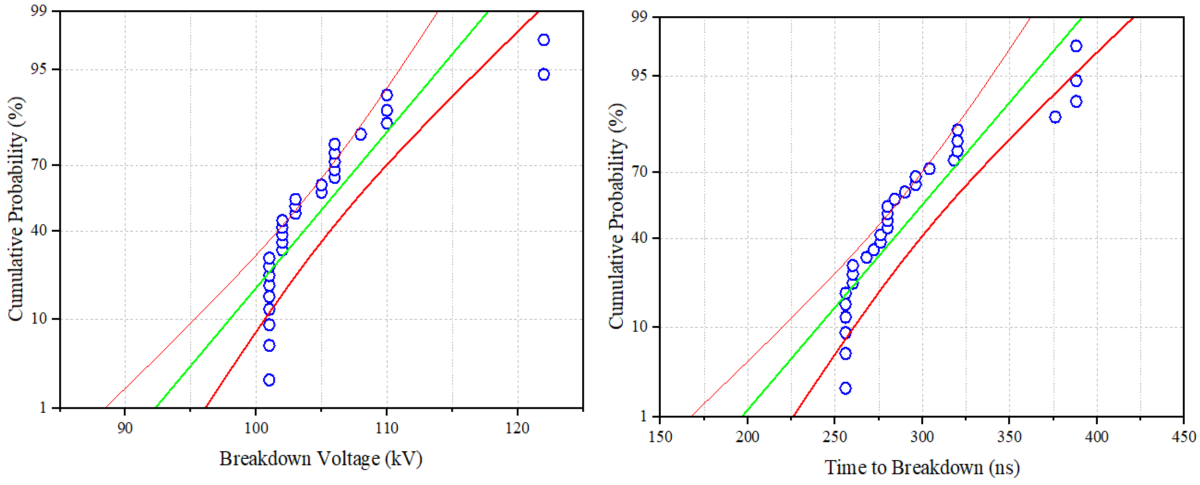


(a) (b)

Figure 4-6; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the synthetic ester samples when stressed with negative lightning impulse can be seen in Figure 4-6a. All samples exhibit a similar level of breakdown voltage with only a 2% difference between the highest (140kV) and lowest (137kV) average values; calculated for Sample 3 and Sample 1 respectively. However, given the overlapping error bars, which represent the 95% confidence intervals, any observed difference in these averages may not represent statistical significance at $\alpha = 0.05$. It is evident from the size of the 95% confidence error bars that breakdown of each liquid sample occurs within a small range of values.

The average time to breakdown of each of the synthetic ester liquid samples under negative voltage stress is, as with the data associated with breakdown under positive impulse, in slight contrast to that of the breakdown voltage. This again can be attributed to the existence of outlying data points within the dataset; supported by the large error bars associated with Sample 1. Time to breakdown data is seen to occur over a much larger range of values (percentage wise) than that of the average breakdown voltage given the much larger error bars present in the data; with this thought to be the cause of the differing behaviour of the two parameters.

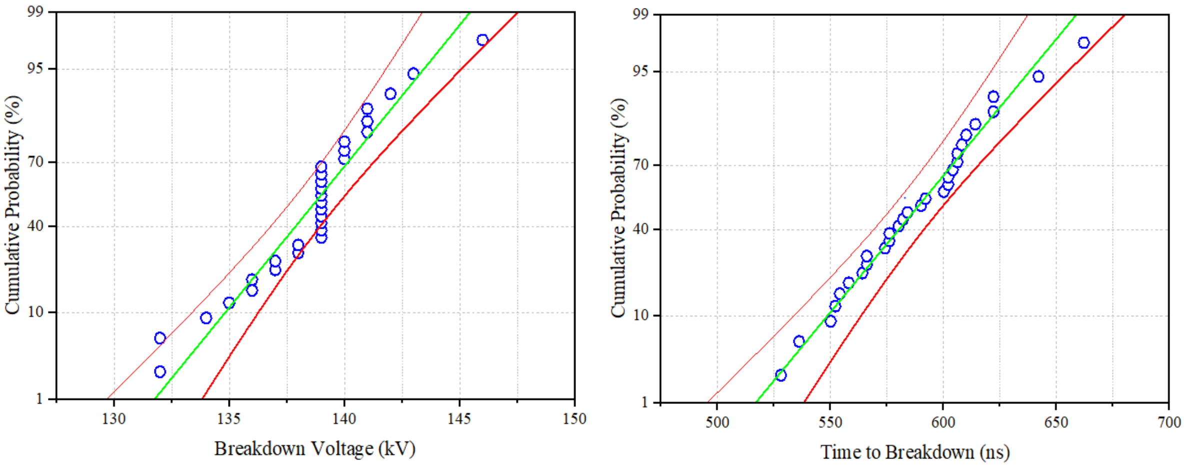


(a) (b)

Figure 4-7; *Probability plots for 'As Received' synthetic ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

When reviewing the CPF of the breakdown voltage of the synthetic ester under positive lightning impulse it is clear that again the plot takes on an unexpected shape. Due to its conformance with the KS normality test (p-value 0.07) the data can be assumed to be distributed normally, however as can be seen a number of data points deviate from the distribution line, with ~16% of the data residing outside of the 95% confidence bands; particularly at the upper and lower extremes of the data. This demonstrates that breakdown of the liquid samples occurred with a small range of values. Despite the profile of the CPF the extraction of the predicted breakdown voltages at the percentiles of interest (10th, 50th and 95th) is still possible with these shown to be 98kV ($V_{10\%}$), 105kV ($V_{50\%}$) and 114kV ($V_{95\%}$).

The CPF generated for the time to breakdown of the synthetic ester can be seen in Figure 4-7b. It is clear that the data better conforms to the expected normal distribution than the associated breakdown voltage data (Figure 4-7a); supported by the higher p-value of the time to breakdown data (0.17 as compared with 0.07). While again ~16% of the data sits outside the upper and lower confidence bands the data within these bands is placed much closer to the normal distribution line at least within the range of the 20th to 40th percentiles. This however does not correspond to the selected percentiles of interest and there is an absence of data points at the upper and lower percentiles (10th and 95th). However, given that the data was shown to be of normal distribution extraction of the predicted time to breakdown was still possible, with values shown to be 135kV ($V_{10\%}$), 139kV ($V_{50\%}$) and 143kV ($V_{95\%}$).



(a)

(b)

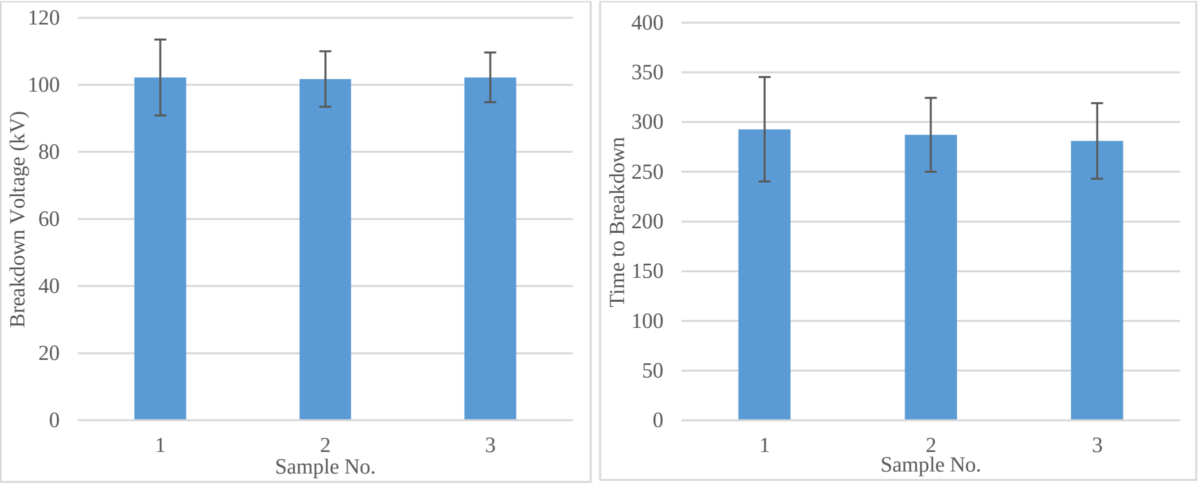
Figure 4-8; *Probability plots for 'As Received' synthetic ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data recorded for the breakdown of the synthetic ester samples under negative lightning impulse was shown to conform to a normal distribution with a KS normality test p-value of 0.09. While this does confirm that the data is distributed normally it is clear from the generated CPF plot that approximately one-third (36%) of the breakdown events occur at a level of breakdown voltage close to the mean breakdown voltage. Unlike the plots produced for the breakdown of the synthetic ester liquid under positive impulse, the vast majority of the data recorded for negative voltage stress resides within the upper and lower confidence bands (95%). Given the closeness of the data points to the normal distribution line extraction of the 10th, 50th and 95th percentiles is possible; with values of 135kV, 139kV and 143kV, respectively, predicted by the CPF.

The CPF produced for the time to breakdown data has a distribution closer to that of the predicted normal distribution; demonstrated by its KS normality test p-value of ~1. Further to this high p-value, it is clear from Figure 4-8b that almost all data sits on the normal distribution line with only two data points in the upper percentiles deviating from this line. This allowed for all percentiles of interest to be extracted with great confidence for the time to breakdown of the synthetic ester liquid under negative lightning impulse. Values at the percentiles of interest, 10th, 50th and 95th, are 549ns, 588ns and 638ns respectively.

4.2.1.3. Breakdown natural ester in the ‘As Received’ condition

The breakdown voltage and associated time to breakdown of the six individual samples of the natural ester Envirotemp FR3 (three samples per impulse polarity) in the ‘As Received’ condition were exposed to positive and negative lightning impulse voltage as described in Section 3.6.1. The level of breakdown voltage for each of the individual natural ester samples was seen to fluctuate up and down across the data series as did the time to breakdown for each shot; this holds true for all samples tested under both positive and negative lightning impulse. The lack of any clear trend in the obtained experimental data under either energisation polarity allowed the sample data to be pooled for CPF analysis (n = 30).

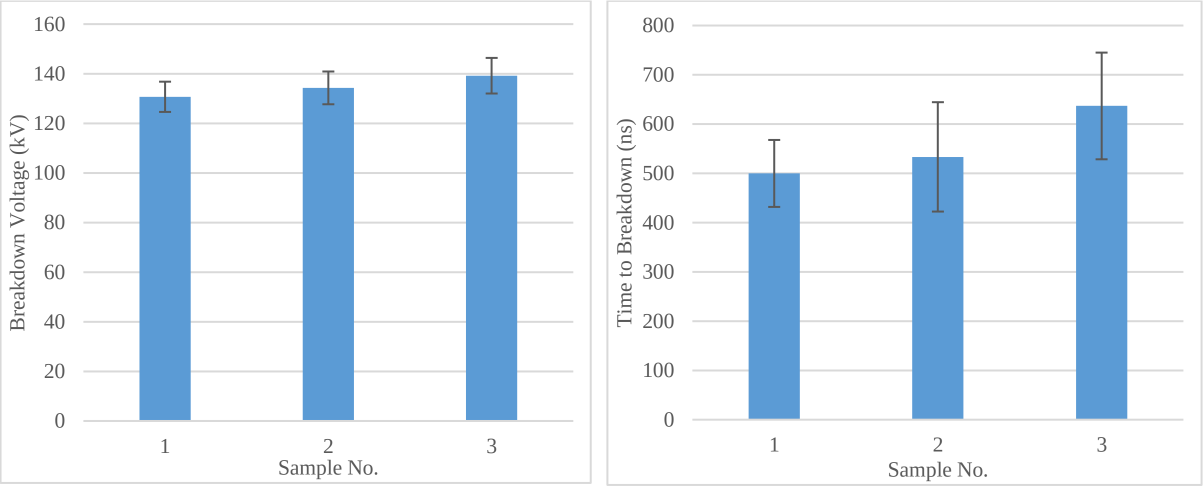


(a) (b)

Figure 4-9; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

As can be seen from the average breakdown voltage data provided in Figure 4-9a all confidence intervals overlap, indicating a likely absence of statistical difference in the level of voltage required to cause breakdown of any of the natural ester samples when the fluid is under positive lightning impulse stress. The difference in average levels of breakdown voltage for each of the three samples is extremely low (~1%). This similarity in breakdown voltage for all samples suggests that the data can be pooled into one single dataset.

Statistical similarity is also probable to exist in the time to breakdown for each of the three samples; again demonstrated by the overlapping 95% confidence intervals. As with the average breakdown voltage, the longest time to breakdown is seen for the data in Sample 1, though unlike the data in Figure 4-9a the shortest time to breakdown relates to that of Sample 2. Given the closeness in average values of breakdown voltage, this contrasting behaviour of time to breakdown can be attributed to slight distortions in the applied impulse waveform.

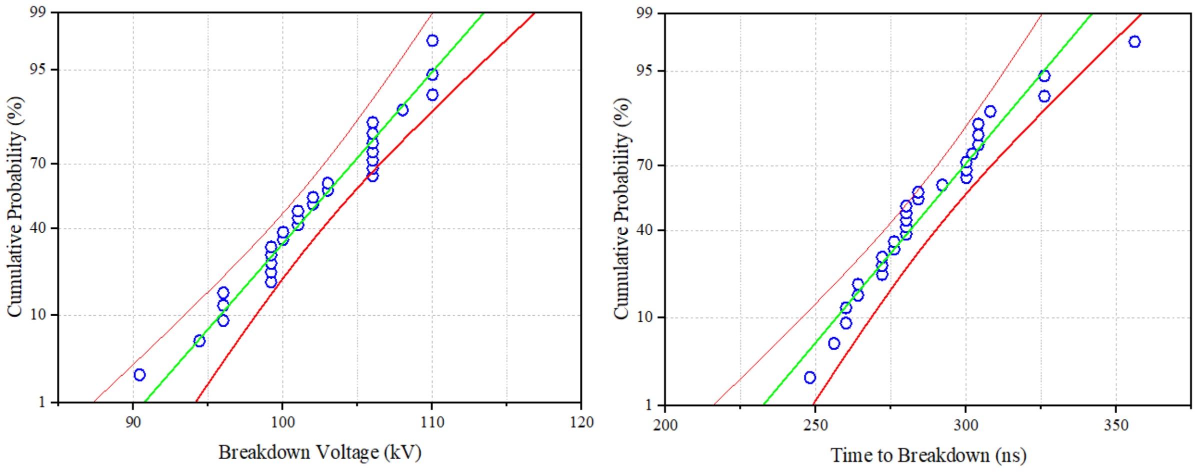


(a) (b)

Figure 4-10; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When the average breakdown voltage data calculated for the natural ester fluid under negative lightning impulse is evaluated, it is clear that breakdown is likely to occur at a statistically similar level of voltage for each of the three samples. Again, as the 95% confidence intervals overlap this data can be pooled together to give a suitably sized dataset for CPF analysis.

The average time to breakdown data relating to the breakdown of the natural ester samples when under negative voltage stress is in good agreement with that of the breakdown voltage, with the longest average time calculated for Sample 3 (637ns) and the shortest for Sample 1 (500ns). While this trend is identical to that of the breakdown voltage, the difference between the highest and lowest values of average time to breakdown is much greater than that of breakdown voltage (22% as compared with 6%). This is attributed to the larger spread of the time to breakdown data as compared with breakdown voltage; visibly demonstrated by the larger error bars that exist for the time to breakdown data.



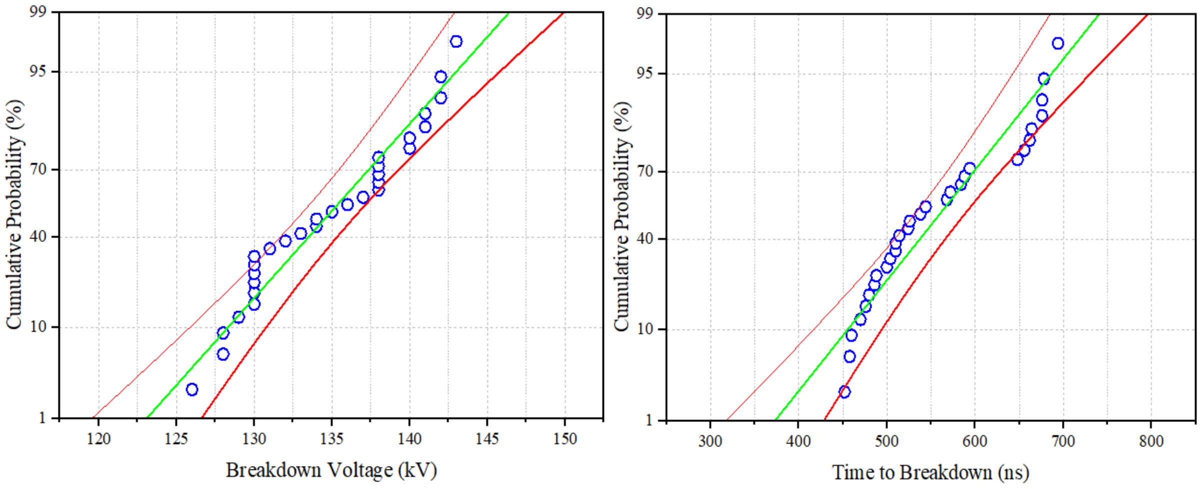
(a)

(b)

Figure 4-11; *Probability plots for 'As Received' natural ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPFs derived from the natural ester Envirotemp FR3 under positive lightning impulse is shown in Figure 4-11. Breakdown voltage (Figure 4-11a) has been shown through the KS normality test to conform to a normal distribution (p-value of 0.41). Data gathered for this parameter shows strong agreement with the distribution at the percentiles of interest (10th, 50th and 95th) but does deviate outside of these percentiles; particularity in the range of the 70th to 80th percentiles. This is due to 23% of the data exhibiting the same breakdown voltage (106kV) residing in this range. For the percentiles of interest predicted breakdown voltage of the natural ester when stressed with positive lightning impulse is 96kV (10th), 102kV (50th) and 110kV (95th).

The CPF for the time to breakdown parameter is shown in Figure 4-11b. Again, the conformity of the data to a normal distribution is assured by the KS normality test (p-value of 0.47). While some data points particularly in the lower and upper extremities of the percentile range deviate from the distribution line the vast majority resides on or close to the predicted distribution, particularly within the percentiles of interest. This allows for accurate derivation of the time to breakdown values at the percentiles of interest, specifically 257ns (10th), 287ns (50th) and 326ns (95th).



(a) (b)

Figure 4-12; *Probability plots for 'As Received' natural ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF for the breakdown voltage data gathered during the testing of the natural ester samples under negative energisation has been provided in Figure 4-12a. The KS normality test was again implemented to assure the conformance of the data to a normal distribution (p-value 0.38). When evaluating the CPF it is clear that data does deviate from the predicted distribution line, particularly in the 20th and 35th percentiles, though still resides with the 95% confidence bands. There is another deviation observed around the 60th percentile; with both of these attributed to a number of breakdown events occurring at the same voltage level (130kV for the deviation in the 20th to 35th percentile and 138kV at the 60th percentile). Despite this migration of the data in the aforementioned areas the data at the percentiles of interest is in good agreement with the predicted distribution and thus allows for accurate extraction of breakdown voltage at these percentiles; namely 128kV (10th), 135kV (50th) and 143kV (95th).

The KS normality test for the time to breakdown of the natural ester fluid under negative lightning impulse demonstrated that the data is again normally distributed (p-value 0.46). Analysis of the CPF generated for the data (Figure 4-12b) clearly shows that the time to breakdown associated with the breakdown of the natural ester fluid is in good agreement with the predicted distribution. The large majority (80%) of the data points reside on, or close, to the normal distribution line and almost all data (90%) is placed within the upper and lower confidence bands. Data in the range of the 10th to 70th and 90th to 95th percentiles can be seen to demonstrate the best adherence to the distribution. This is attributed to the large spread of the time to breakdown data, which is in contrast to that of the breakdown voltage gathered for samples under negative lightning impulse (Figure 4-11a). At the percentiles of interest (10th, 50th and 95th), the predicted time to breakdown of the natural ester fluid is 456ns, 557ns and 687ns respectively.

4.2.1.4. Summary of breakdown of dielectric fluids in ‘As Received’ condition

Data has been presented on the breakdown of the three chosen dielectric fluids when in ‘As Received’ condition under lightning impulse voltage of both positive and negative polarity. The average breakdown voltage and associated time to breakdown of each of the fluids, as well as the cumulative probability function of the data under both energisation polarities, was analysed with this data summarised in Table 4-1

Table 4-1; *Average breakdown voltage and time to breakdown of 'As Received' dielectric fluids when stressed with lightning impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	124 ± 14.3kV	113kV	138kV	0.8
	MIDEL 7131	105 ± 9.3kV	98kV	114kV	0.07
	Envirotemp FR3	102 ± 8.3kV	96kV	110kV	0.41
Negative impulse	Shell Diala S4	143 ± 2.6kV	141kV	146kV	0.1
	MIDEL 7131	139 ± 5.0kV	135kV	143kV	0.09
	Envirotemp FR3	135 ± 8.5kV	128kV	143kV	0.38
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	423 ± 123ns	331ns	542ns	0.64
	MIDEL 7131	294 ± 71ns	240ns	367ns	0.17
	Envirotemp FR3	287 ± 40ns	257ns	326ns	0.47
Negative impulse	Shell Diala S4	1255 ± 357ns	986ns	1600ns	~1
	MIDEL 7131	588 ± 52ns	549ns	638ns	~1
	Envirotemp FR3	557 ± 134ns	456ns	687ns	0.46

Table 4-1 provided information on the average breakdown voltage and time to breakdown of the chosen dielectric fluids in the ‘As Received’ condition under both positive and negative lightning impulse. The stated average values, V_{mean} and t_{mean}, of a given parameter ± the 95% confidence interval as calculated from the entire dataset (n = 30) for a given liquid and impulse polarity are provided. $V_{10\%}$ to $V_{95\%}$ represent the probability values of the breakdown parameters for a given liquid as predicted by the CPF, with the p-values produced from the KS goodness of fit test also included. When examining the average breakdown voltage and time to breakdown for the three dielectric liquids under lightning impulse stress it is clear that breakdown occurs at a statistically similar level of voltage, and time to breakdown, for all tested fluids under positive energisation. This also holds true for the breakdown voltage parameter under negative impulse stress, however, not in the case of the time to breakdown parameter. The data provided in Table 4-1 clearly shows that the breakdown of the mineral oil requires a longer time than that of both the ester fluids; for which no statistical difference exists in time to breakdown. It can also be said that breakdown of all fluids under negative energisation consistently occurs at a higher level of breakdown voltage and longer time to breakdown than when the impulse is positive. Under both positive and negative impulse, the mineral oil Shell Diala S4 is seen to possess the highest average breakdown voltage and longest time to breakdown, with the natural ester Envirotemp FR3 shown to exhibit the lowest values for both these breakdown parameters.

Evaluation of the values of breakdown voltage extracted from the CPFs for the fluids under positive impulse stress shows that the breakdown of the ester fluids occurs over a much smaller range of voltages than that of the mineral oil; with this mirrored in the data pertaining to the predicted time to breakdown. When under such positive impulse stress breakdown voltage, and associated time to breakdown, of the mineral oil is predicted by the CPF to be higher than that of both esters at all percentiles of interest. As with average breakdown voltage and time to breakdown, the natural ester is again shown to possess the lowest values of the examined breakdown parameters.

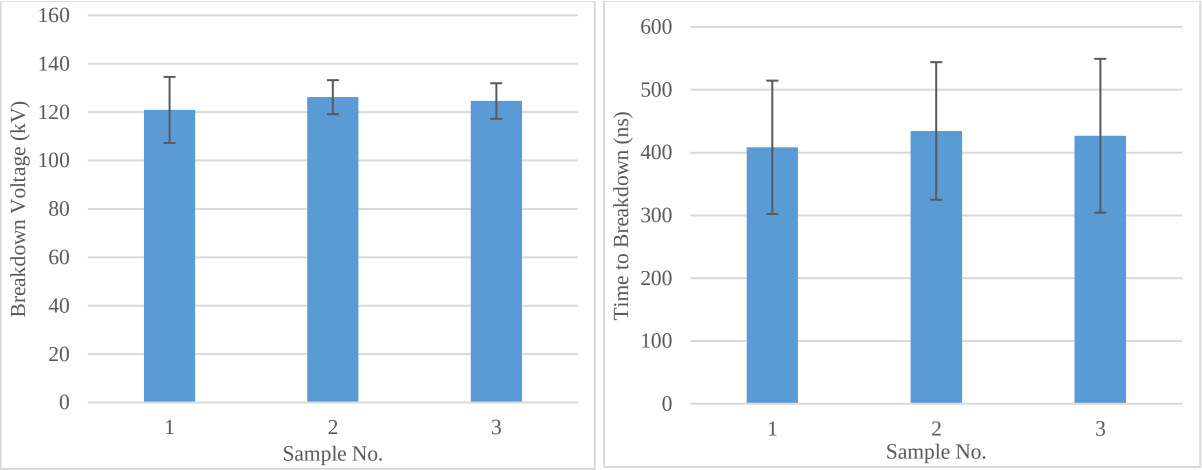
In contrast to the behaviour of the fluids observed under positive impulse, when the fluids are stressed with negative lightning impulse examination of the CPF data shows that the breakdown of the mineral oil now occurs over the smallest ranges of values; with that of the natural ester the largest. This however is not seen in the time to breakdown data where, as with that under positive stress, values of this parameter occur over the widest range for the mineral oil. This change in behaviour between predicted values of breakdown voltage and time to breakdown for the mineral oil can be assumed to be because of the breakdown of the fluid taking place near the peak of the voltage impulse where the change in voltage is low while that of the time parameter is much greater.

4.2.2. Breakdown of liquids in the ‘Ambient humidity’ condition

The proceeding sections present and discuss the results pertaining to the bulk breakdown performance of the chosen dielectric fluids in the ‘Ambient humidity’ condition. Fluids in this state possess relative humidity of ~35%. As described in Section 3.3.1, the desired level of relative humidity was achieved by allowing the fluids, which were in open containers, to sit within the laboratory environment until the relative humidity of the fluid reached equilibrium with ambient levels.

4.2.2.1. Breakdown of mineral oil in the 'Ambient humidity' condition

When the breakdown voltage and associated time to breakdown measured for each shot applied to the three mineral oil samples was examined, there was no clear trend in either breakdown parameter. Both upward and downward variations were observed across the datasets (shot 1 to shot 10) for each of the three tested samples, irrespective of the polarity of the energising impulse. Absence of any discernible trend meant that the breakdown voltage and time to breakdown associated with each breakdown event experienced by a given sample could be pooled to create three discrete datasets, one for each sample, consisting of ten measurements (n = 10). These larger datasets were then used for the purpose of mean value analysis.

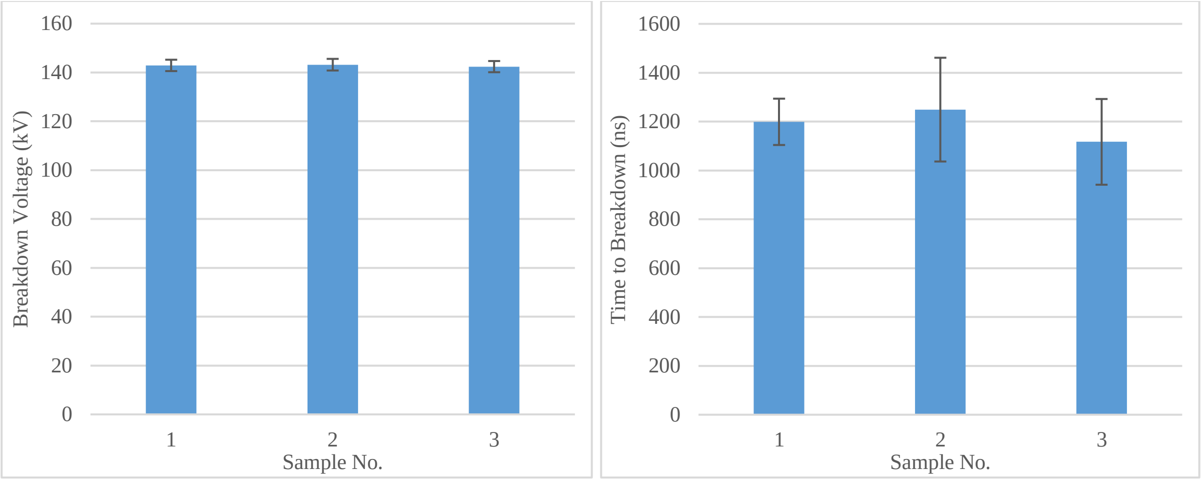


(a) (b)

Figure 4-13; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage, and the 95% confidence intervals, of each of the three mineral oil samples in the 'Ambient humidity' condition can be seen in Figure 4-13a. It is clear from the data presented that all confidence intervals overlap and thus statistically significant difference (at the selected degree of confidence) may not exist in the average breakdown voltage of the three samples under positive lightning impulse stress. Breakdown of each of the liquid samples occurs at a similar level of voltage with only a 4% difference between the highest (126kV) and lowest (121kV) values of average breakdown voltage. Given this low variance in average values of breakdown voltage, as well as the overlapping confidence intervals, it is reasonable to pool this data into a 30-point dataset for further statistical analysis.

The data obtained relating to the time to breakdown of the mineral oil samples under positive lightning impulse voltage (Figure 4-13b) shows identical behaviour to that of the breakdown voltage (Figure 4-13a). Again, the overlapping 95% confidence intervals indicate that statistical difference between the sample means may not exists at the selected degree of confidence. One difference observed with the time to breakdown data is that measured values of this breakdown parameter occur over a wider range than that of the breakdown voltage. This is demonstrated by the much larger size of the error bars associated with the time to breakdown data.

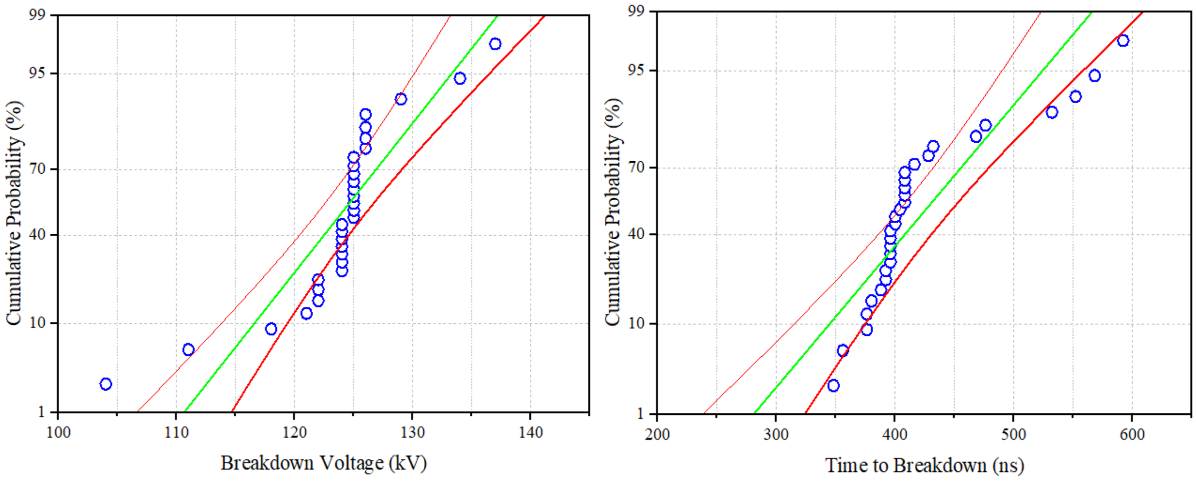


(a) (b)

Figure 4-14; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When evaluating the average breakdown voltage obtained for the mineral oil samples stressed with negative lightning impulse (Figure 4-14a) the overlapping confidence intervals imply that breakdown is likely to occur at a statistically similar level of voltage for all samples. It is also clear from the data presented in Figure 4-14a that breakdown of the samples occurs over a very small range of voltage values (142kV to 143kV), confirmed by the small size of the confidence interval error bars. This is because of breakdown of the mineral oil samples under negative impulse taking place close to the peak of the voltage impulse for almost every shot applied to the liquid sample.

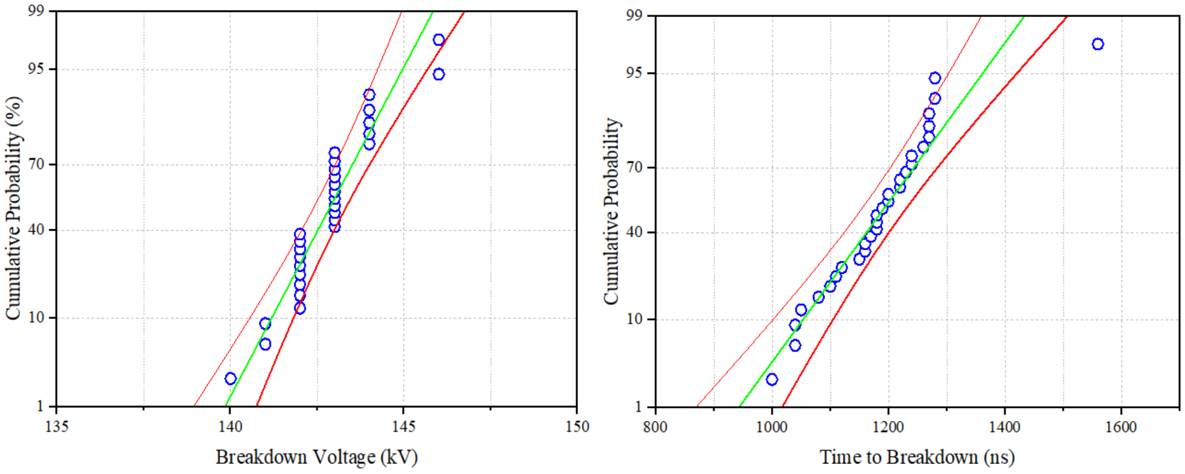
The time to breakdown data obtained when the mineral oil samples were stress with negative lightning impulse (Figure 4-14b) shows similar behaviour to that of the breakdown voltage data, though with a greater degree of difference between average values (11% as compared with 1% for the voltage data). This again supports the observation that breakdown occurs near the peak of the voltage impulse where time is seen to vary much more than voltage. As with the breakdown voltage data, the time to breakdown of the individual liquid samples can be assumed to be absent of statistical difference given the overlap in the 95% confidence error bars. The size of these error bars also show that the time it takes for breakdown of the samples to occur is spread over a much wider range of values than that of the breakdown voltage; further supporting that the breakdown of the mineral oil under negative energisation occurs near the peak of the voltage impulse.



(a) (b)

Figure 4-15; *Probability plots for 'Ambient humidity' mineral oil; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

Both breakdown voltage and time to breakdown of the mineral oil in the 'Ambient humidity' condition when under positive lightning impulse do not meet the KS normality test criteria and thus the normal distribution of the data must be rejected. Therefore, the data pertaining to the predicted values of breakdown voltage and time to breakdown at the percentiles of interest cannot be extracted from the above CPFs (Figure 4-15a and 4-15b).



(a) (b)

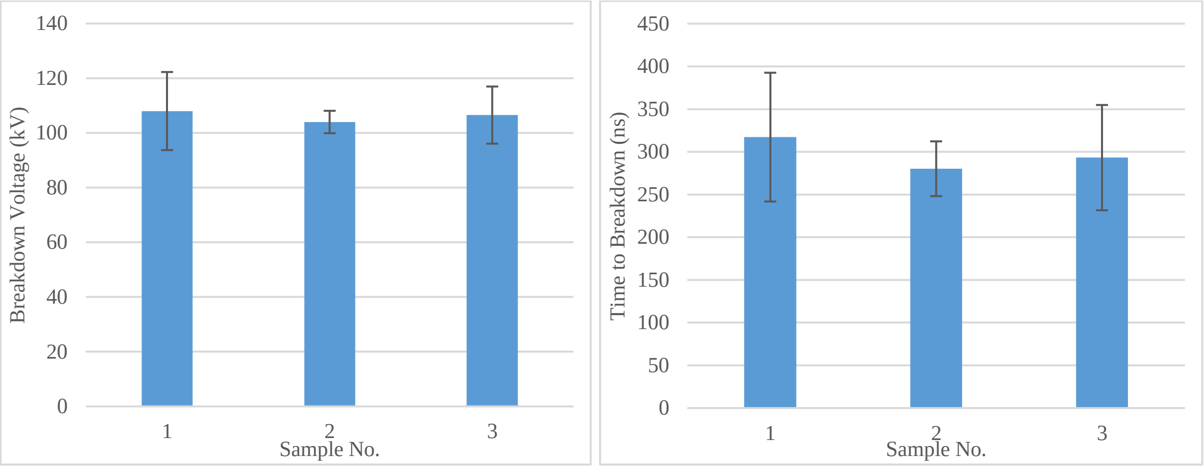
Figure 4-16; *Probability plots for 'Ambient humidity' mineral oil; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF generated from the breakdown voltage data obtained during the testing of the 'Ambient humidity' condition mineral oil under negative lightning impulse stress has been given in Figure 4-16a. The normal distribution of the data was confirmed by the KS normality test (p-value 0.11). It is clear from the CPF that breakdown of the mineral oil occurs mainly at three voltage levels 142kV (30% of all breakdowns), 143kV (~37% of all breakdowns) and 144kV (~17% of all breakdowns). This has resulted in the unusual profile depicted in the CPF with clear straight lines present at the aforementioned voltage levels. There does however exist data points on the predicted normal distribution line at all but the highest percentile of interest. The predicted values of breakdown voltage that can be extracted for the 10th, 50th and 95th percentiles are 141kV, 143kV and 145kV respectively.

The CPF produced from the time to breakdown data gathered during the negative impulse testing of mineral oil in the 'Ambient humidity' condition (Figure 4-16b) shows a much more expected shape; with the majority of the data (70% of all data points) residing on the normal distribution line. This is confirmed by the KS normality test for which a p-value of ~0.4 was calculated. Again, there is a deviation from the predicted distribution at the highest percentile of interest (95th) with data in this region existing outside of the upper and lower 95% confidence bands. Despite the profile of the data in the CPF, as with that generated from the breakdown voltage data, the predicted values for time to breakdown at the 10th, 50th and 95th percentiles can be taken; 1053ns, 1188ns and 1362ns respectively.

4.2.2.2. Breakdown of synthetic ester in the 'Ambient humidity' condition

In this section, the breakdown of the synthetic ester MIDEL 7131 in the 'Ambient humidity' condition (relative humidity ~35%) will be discussed. Evaluation of the breakdown voltage and time to breakdown of the synthetic ester under both positive and negative lightning impulse showed that no discernible upward or downward trend existed in the experimental data. This allowed for the ten individual breakdowns of each sample to be pooled together to produce three discrete datasets (n = 10) one for each liquid sample.

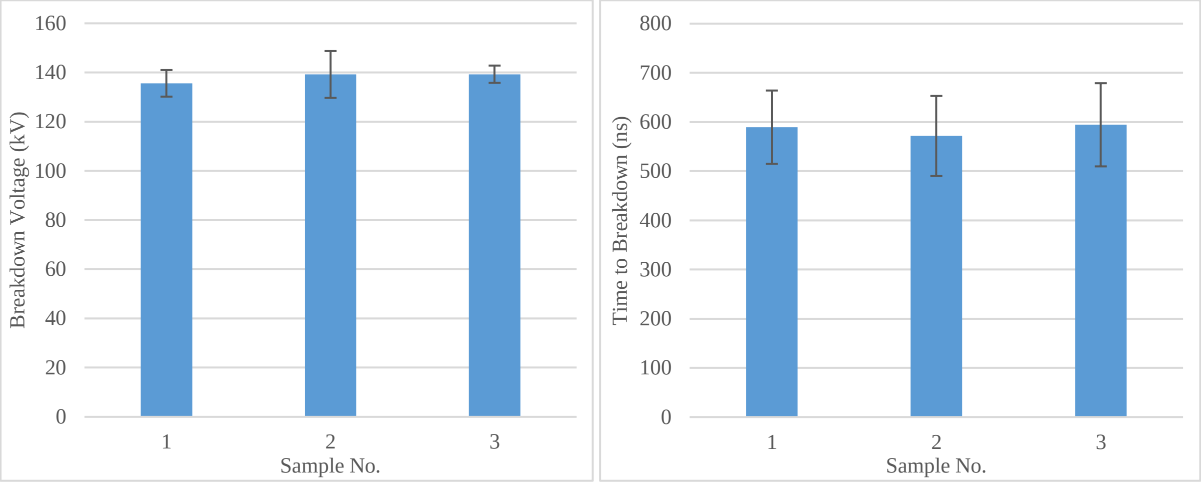


(a) (b)

Figure 4-17; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The overlapping of the confidence intervals again shows that statistical difference in the values of average breakdown voltage calculated for each of the three 'Ambient humidity' samples of synthetic ester under positive lightning impulse may not exist at the selected degree of confidence; apparent upon review of Figure 4-17a. This likely absence of statistical difference between samples therefore allows for the datasets to be pooled together for CPF analysis.

The time to breakdown data associated with the breakdown of the synthetic ester samples under positive lightning impulse shows identical behaviour to that of the breakdown voltage data. The difference which exists in the average values time to breakdown however is greater than that present in the breakdown voltage data (~12% as compared with ~6%). It must be said though that due to the overlapping confidence intervals this aforementioned difference may not be of statistical significance (at the selected degree of confidence).

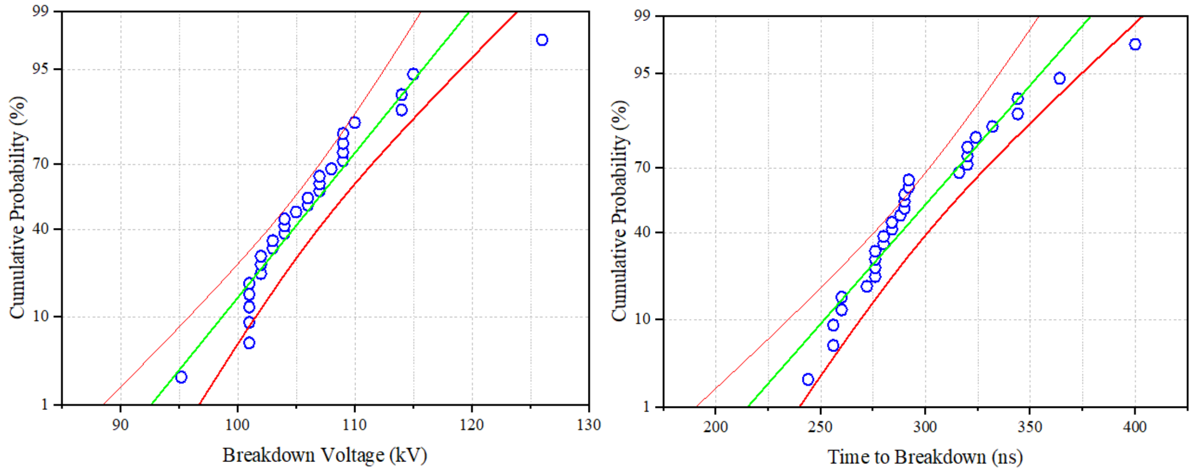


(a) (b)

Figure 4-18; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When examining the data pertaining to the average breakdown voltage of each of the synthetic ester samples under negative lightning impulse it can again be said that it is unlikely that statistical difference exists between the mean breakdown voltage values for each sample. Again, the spread of the data recorded for each liquid sample is low (with the largest occurring in the data associated with Sample 2). Although as with the breakdown voltage of the samples under positive impulse, again the variation in average values (reflected in the size of the 95% confidence intervals) is of sufficient magnitude that statistical difference at the selected degree of confidence may not be present between samples.

Review of the average time to breakdown data for each of the liquid samples shows that again statistical variation at the selected degree of confidence may not exist between samples. However, unlike the data on average breakdown voltage, the longest time to breakdown does not occur for Sample 2, rather Sample 3 (594ns). Sample 2 is now seen to have the shortest average time to breakdown (572ns). This can be attributed to the wider spread of the values within the Sample 2 dataset which clearly contains outliers; this is supported by the large error bars associated with the Sample data (the largest of the three samples).

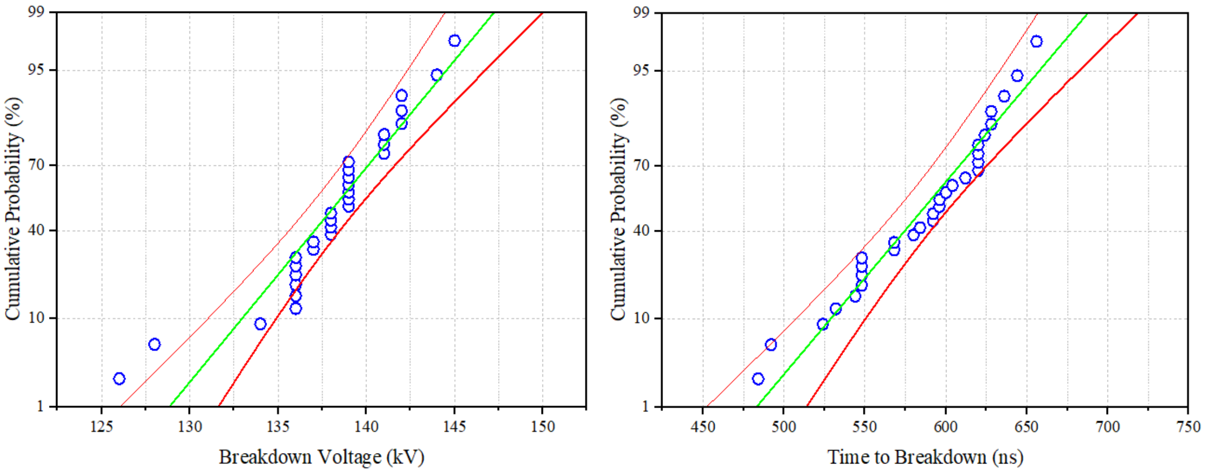


(a) (b)

Figure 4-19; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The normal distribution of the breakdown voltage data gathered during the positive lightning impulse testing of the synthetic ester in the 'Ambient humidity' condition, presented in the CPF (Figure 4-19a), was confirmed by means of the KS normality test (p-value 0.43). As is evident from Figure 4-19a the vast majority (~76%) of the data resides on, or close to, the normal distribution line, with all but two data points in the upper, and lower, most percentiles contained within the confidence bands. Given the good agreement between the measured experimental data and the normal distribution line, predicted values of breakdown voltage can be extracted at all percentiles of interest 99kV (10th); 106kV (50th) and 116kV (95th).

The distribution of the time to breakdown data was also subjected to the KS normality test with normal distribution confirmed (p-value 0.09). As can be seen from Figure 4-19b data does deviate from the predicted distribution line more than that of the CPF of breakdown voltage (Figure 4-19a) with four data points outside the confidence bands. Experimental data at the percentiles of interest lie close to the predicted distribution line and thus can be taken with some confidence; 252ns (10th), 297ns (50th) and 355ns (95th).



(a) (b)

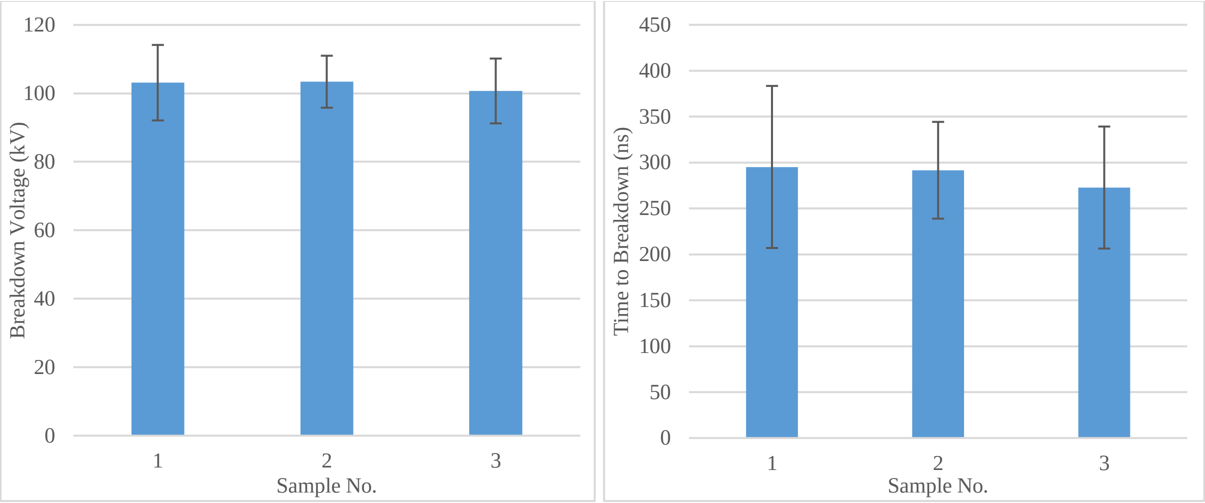
Figure 4-20; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data gathered during the testing of the synthetic ester under negative lightning impulse has been shown to be normally distributed (p-value 0.15). While the large majority (86%) of the data lies within the confidence bands the profile of the CPF does not follow the distribution line as would be expected. From the CPF, shown in Figure 4-20a, it is clear that breakdown predominately occurs at five voltage levels across a very narrow range; 136kV, 138kV, 139kV, 141kV and 142kV. The predicted values at the percentiles of interest are shown to be 133kV (10th), 138kV (50th) and 145kV (95th).

The normally distributed time to breakdown data (p-value 0.69) can be seen in the CPF in Figure 4-20b. The obtained experimental data is closely aligned with the predicted distribution with most data points on, or close to, the reference line. Two straight lines do appear in the profile of the CPF, however these do not occur at the percentiles of interest. Thus, predicted values of time to breakdown can be taken with confidence at all key percentiles; 529ns (10th), 585ns (50th) and 658ns (95th).

4.2.2.3 Breakdown of natural ester in the 'Ambient humidity' condition

The section which follows will present and discuss the results gathered from the breakdown testing of the natural ester Envirotemp FR3 when in the 'Ambient humidity' condition (relative humidity ~35%). The mean breakdown voltage and time to breakdown of the liquid samples will be presented along with the CPFs produced from the obtained experimental data. Examination of the data showed that no trend exists in each of the breakdown parameters under either positive or negative lightning impulse stress. This allowed for the pooling of the experimental data gathered for each of the liquid samples to produce three datasets each consisting of ten separate breakdown events.

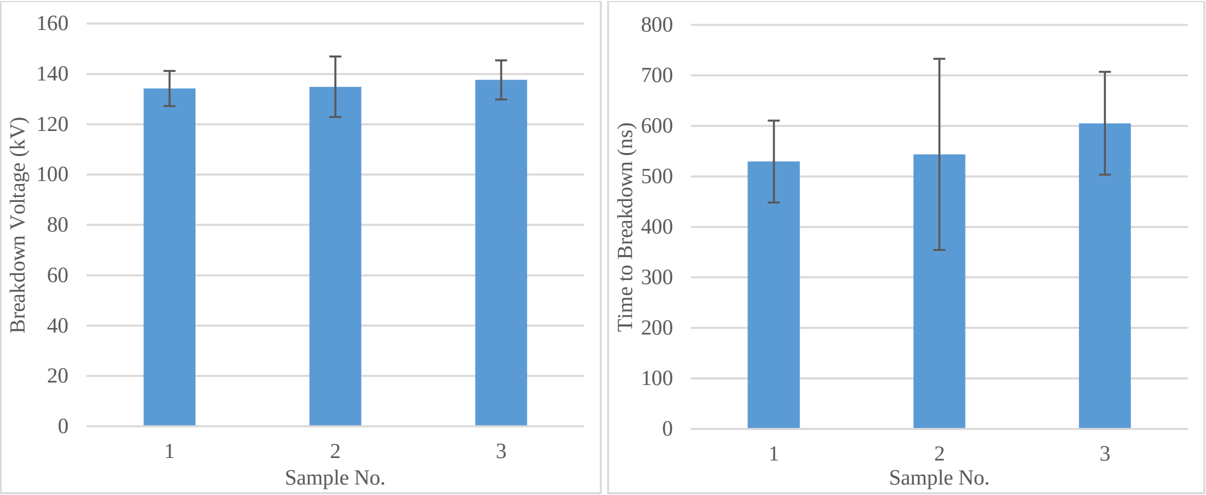


(a) (b)

Figure 4-21; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages calculated for each of the three natural ester samples under positive lightning impulse have been given in Figure 4-21a. From the figure it is clear that each of the three sample confidence intervals overlap and thus that breakdown is likely to occur at a statistically similar level of voltage for each of the three samples. The spread of the data (error bar size) is similar for all three samples, this shows that the natural ester samples exhibit consistent behaviour under application of positive lightning impulse. Given the aforementioned overlapping of the 95% confidence error bars, it is reasonable to pool the data obtained from the three samples into a larger data set (n = 30) for means of probability analysis.

The time to breakdown data (Figure 4-21b) is in mild conflict to that of the breakdown voltage. While the shortest time to breakdown is, as expected, observed for Sample 3 (273ns) the longest average time to breakdown was calculated for Sample 1 (295ns), rather than Sample 2 (292ns) which had the highest average breakdown voltage. This observation can be explained by the much larger error bars associated with the time to breakdown data for Sample 1 showing that outliers exist within this dataset and subsequently result in a slightly higher average value than that of Sample 2. These differences however may not be statistically significant at the selected degree of confidence given the overlapping of the 95% confidence intervals.

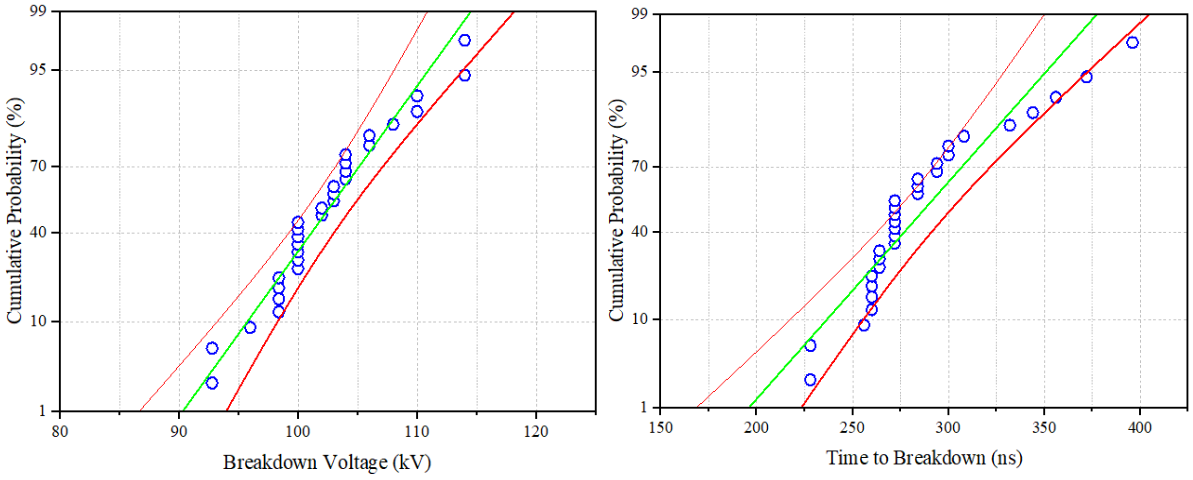


(a) (b)

***Figure 4-22;** Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

From the data presented in Figure 4-22a it can be assumed that the breakdown of each of the three natural ester samples occurs at a similar voltage level. Statistical difference may not exist (at the selected degree of confidence) between the average breakdown voltages of each of the samples due to the overlap in all confidence intervals. Again, as the 95% confidence error bars overlap for all three samples this data can be pooled to create a suitably large dataset to perform cumulative probability analysis.

Examining of the time to breakdown data (Figure 4-22b) shows that identical trends exist in this data as do in that of the breakdown voltage; with statistical difference in calculated average values between samples unlikely. However, the difference in the average time to breakdown values is much larger than is observed in the breakdown voltage data (13% as compared with 3%). This can be explained by the much larger error bars which have been calculated for the time to breakdown data highlighting the existence of outlying data points causing the distortion of the calculated average values.



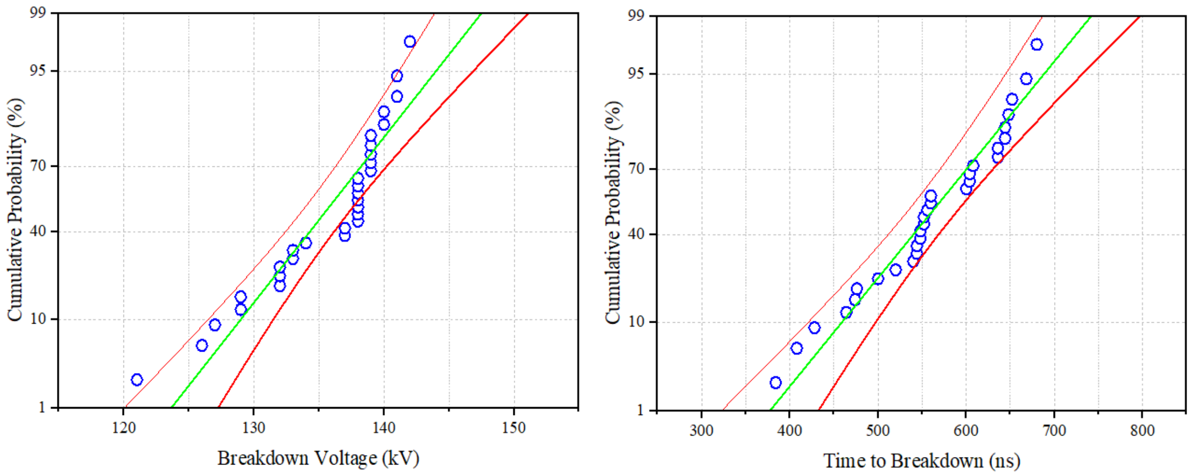
(a)

(b)

Figure 4-23; *Probability plots for 'Ambient humidity' natural ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from the experimental data obtained during testing of the natural ester in 'Ambient humidity' condition under positive lightning impulse has been given in Figure 4-23a. The data was subjected to the KS normality test and shown to be normally distributed (p-value 0.5) with all data points residing within the upper and lower confidence bands. The CPF does contain some data arranged in vertical lines at 98kV, 100kV and 104kV, demonstrating that breakdown occurred at the same level of voltage for a number of individual shots. That said, at all but the upper percentile of interest (95th) data points lie on the normal distribution line, allowing for the extraction of predicted values of breakdown voltage; 96kV ($V_{10\%}$), 102kV ($V_{50\%}$) and 111kV ($V_{95\%}$).

When examining the CPF derived for the time to breakdown it can be seen that there is much more deviation from the normal distribution line than is present in that of the breakdown voltage. Although the data can still be said to be distributed normally given its conformance with the KS normality test criteria (p-value 0.12). Again, there are vertical lines present in the data showing that a number of breakdown events share the same time delay. Despite the profile of the CPF and the deviation of the data from the distribution reference line, the predicted values of time to breakdown for the natural ester under positive lightning impulse are 237ns ($t_{10\%}$), 287ns ($t_{50\%}$) and 350ns ($t_{95\%}$).



(a)

(b)

Figure 4-24; *Probability plots for 'Ambient humidity' natural ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF generated from the experimental data obtained when the natural ester samples were stressed with negative lightning impulse can be seen in Figure 4-24a. After subjecting the data to the KS normality test it was shown that the data was not distributed normally (p-value 0.04), thus the predicted values of breakdown voltage at the percentiles of interest cannot be taken and thus will not be discussed.

Testing of the CPF produced from the time to breakdown data associated with the breakdown of the natural ester under negative lightning impulse (Figure 4-24b) did, unlike that pertaining to breakdown voltage, show conformance to a normal distribution (p-value 0.61). All data points are seen to reside within the confidence bands on, or close to, the distribution reference line. This allowed for extraction of the time to breakdown at all percentiles of interest; 459ns (10th), 559ns (50th) and 688ns (95th).

4.2.2.4. Summary of breakdown of dielectric liquids in the 'Ambient humidity' condition

The chosen dielectric liquids in the 'Ambient humidity' condition were stressed with lightning impulses of both positive and negative polarity. Obtained experimental data for each of the three individual samples of the dielectric fluids was evaluated and it was shown that no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, existed; irrespective of energisation polarity. Evaluation of the mean values of this data demonstrated statistical difference (at the selected degree of confidence) may not exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the three datasets for the means of cumulative probability analysis.

Table 4-2; *Average breakdown voltage and time to breakdown of 'Ambient humidity' dielectric fluids when stressed with lightning impulse. N/A represents data shown to not be of normal distribution.*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	124 ± 9.7kV	N/A	N/A	<0.01
	MIDEL 7131	106 ± 9.9kV	99kV	116kV	0.43
	Envirotemp FR3	102 ± 8.8kV	96kV	111kV	0.5
Negative impulse	Shell Diala S4	143 ± 2.2kV	141kV	145kV	0.11
	MIDEL 7131	138 ± 6.7kV	133kV	145kV	0.15
	Envirotemp FR3	136 ± 8.7kV	N/A	N/A	0.04
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	423 ± 104ns	N/A	N/A	<0.01
	MIDEL 7131	297 ± 60ns	252ns	355ns	0.09
	Envirotemp FR3	287 ± 66ns	237ns	350ns	0.12
Negative impulse	Shell Diala S4	1188 ± 179ns	1053ns	1362ns	0.4
	MIDEL 7131	585 ± 75ns	529ns	658ns	0.69
	Envirotemp FR3	599 ± 133ns	459ns	688ns	0.61

When evaluating the mean values of both breakdown voltage and time to breakdown it is unlikely that statistical difference is present between the ‘Ambient humidity’ liquids for either of the breakdown parameters providing the applied impulse is of positive polarity. This can also be said for the mean breakdown voltage of the three dielectric fluids under negative energisation. However, a statistically significant difference does exist in the time taken to breakdown the fluids, with the mineral oil requiring a significantly longer time to breakdown than both ester liquids (which exhibit a likelihood of statistical similarity in required time to breakdown).

Under positive impulse, it was not possible to use the CPF to predict the levels of voltage required to cause breakdown of the mineral oil given the non-conformance of the data to a normal distribution. When comparing the values predicted for the two ester fluids it is clear they exhibit similar dielectric performance with only a 4% difference in predicted values at all percentiles of interest. When the impulse was of negative polarity it has been shown that the mineral oil offers a higher level of breakdown voltage than that of the synthetic ester at all but the highest percentile of interest (95th). Furthermore, the breakdown of the mineral oil occurs over a much narrower range than the synthetic ester; however, this can be attributed to the breakdown of the mineral oil taking place on, or close, to the peak of the applied impulse. Prediction of the level of voltage required to cause breakdown of the natural ester under negative impulse was not possible given that the data was not distributed normally.

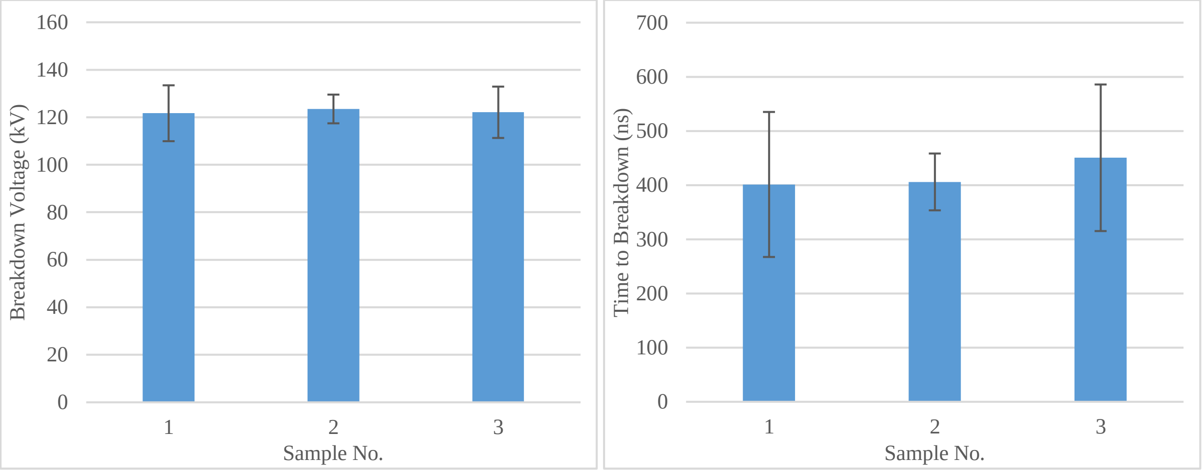
When the predicted values of time to breakdown, taken from each CPF, are examined, it is clear that under positive impulse the synthetic and natural ester fluids offer comparable performance at all percentiles of interest; though with the synthetic ester exhibiting a slightly (~5%) longer time to breakdown. This is also the case under negative energisation, where the synthetic ester is again shown to require a longer predicted time to breakdown at the low and medium percentiles but not at the highest. This can assumed to be as a result of a larger spread of the experimental data gathered for the natural ester fluid; which is supported by the much larger error which is associated with the mean time to breakdown of this fluid. As with breakdown voltage, it was not possible to obtain predicted values of time to breakdown for the mineral oil under positive impulse stress due to the data failing to be distributed normally. It was however possible to obtain predicted values for the time to breakdown of the mineral oil under negative impulse stress with the fluid consistently exhibiting longer predicted times than both ester fluids. It can be seen from the data provided in Table 4-2 that at all percentiles of interest the predicted values of the time to breakdown associated with the mineral oil are almost twice that of both ester fluids.

4.2.3. Breakdown of liquids in the 'Elevated humidity' condition

The following sections of this chapter are devoted to the discussion of experimental data obtained from testing of the chosen dielectric liquids in the 'Elevated humidity' condition. This state denotes liquids with the highest level of relative humidity investigated in this thesis (>70% relative humidity). To achieve such a high state of relative humidity the liquids were subjected to a humidification process; as described fully in Section 3.3.1.

4.2.3.1 Breakdown of mineral oil in the 'Elevated humidity' condition

Examination of the breakdown voltage and time to breakdown data obtained for the 'Elevated humidity' mineral oil samples has shown that no clear trend exists across the ten breakdowns of each sample. This absence of discernible trends within the data has allowed for the grouping of sample data into three discrete datasets each consisting of ten breakdowns for use in mean value analysis.

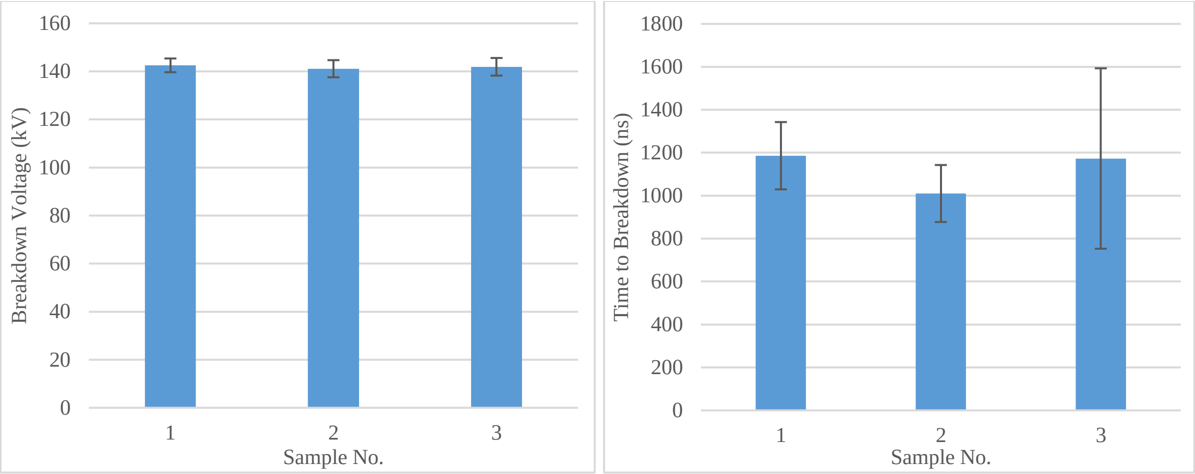


(a) (b)

Figure 4-25; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The data obtained during the testing of the mineral oil samples in the 'Elevated humidity' condition under positive lightning impulse shows that statistical difference in the breakdown voltage of each of the three individual liquid samples (Figure 4-25a) may not be present at the selected degree of confidence. Due to the overlapping of the 95% confidence intervals grouping of the three sample datasets into a larger single dataset is possible with this to be used for the means of cumulative probability analysis.

Evaluation of the data recorded on the time to breakdown of the three individual mineral oil samples (Figure 4-25b) again shows that statistical variation between samples is unlikely. As with the data shown in Figure 4-25a the shortest average time to breakdown is calculated for Sample 1 (401ns), however, unlike the breakdown voltage, the longest average time to breakdown is now seen to occur in Sample 3 (451ns). This discrepancy is thought to result from a greater spread of the Sample 3 time to breakdown data, which is supported by the larger error bars associated with this dataset.

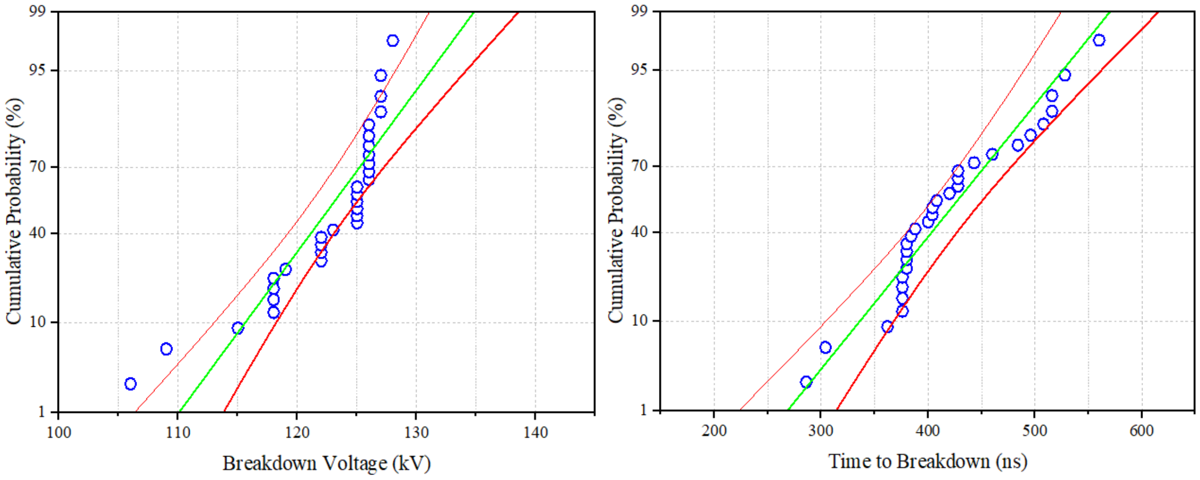


(a) (b)

Figure 4-26; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the three mineral oil samples when stressed with negative lightning impulse can be seen in Figure 4-26a. It can be assumed that breakdown of the samples is likely to occur at a statistically similar level of voltage given the overlap in the 95% confidence intervals. This likely lack of statistical difference in the calculated average values of breakdown voltage facilitates the grouping of the three datasets into one dataset to be used in CPF analysis.

The average time to breakdown for each of the mineral oil samples is in good agreement with that of the breakdown voltage; with the longest average time to breakdown (1186ns) occurring for Sample 1 and Sample 2 the shortest (1010ns). While this difference is larger than that observed in the breakdown voltage data (15% as compared with 2%) a statistically significant difference at the selected degree of confidence may not exist in the calculated average values of time to breakdown for the three samples and therefore grouping of the datasets is possible for the means of CPF analysis.

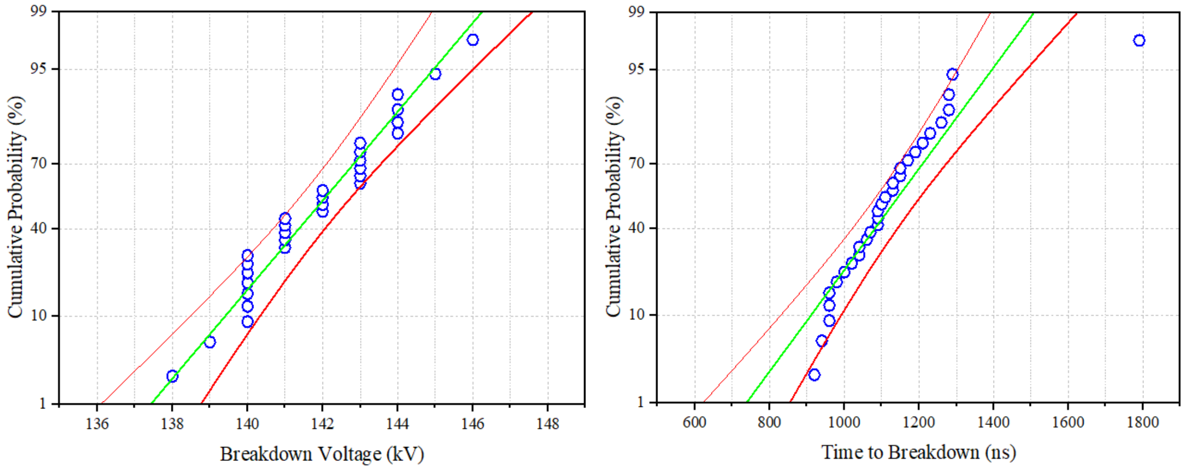


(a) (b)

Figure 4-27; *Probability plots for 'Elevated humidity' mineral oil; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

Evaluation of the CPF produced from the experimental data obtained during the testing of the mineral oil under positive lightning impulse (Figure 4-27a) using the KS normality test demonstrated that the data is not distributed normally (p-value 0.04) and thus prediction of breakdown voltage is not possible.

This is not the case for the CPF generated from the time to breakdown data, which does show conformance to a normal distribution (p-value 0.45). All experimental data points are seen to reside within the 95% confidence banding, with the majority on, or close, to the predicted normal distribution line. There is however, deviation from this reference line at the lower percentile of interest (10th) but in spite of this extraction of predicted values of time to breakdown at the 10th, 50th and 95th percentiles is possible; 335ns, 419ns and 526ns respectively.



(a) (b)

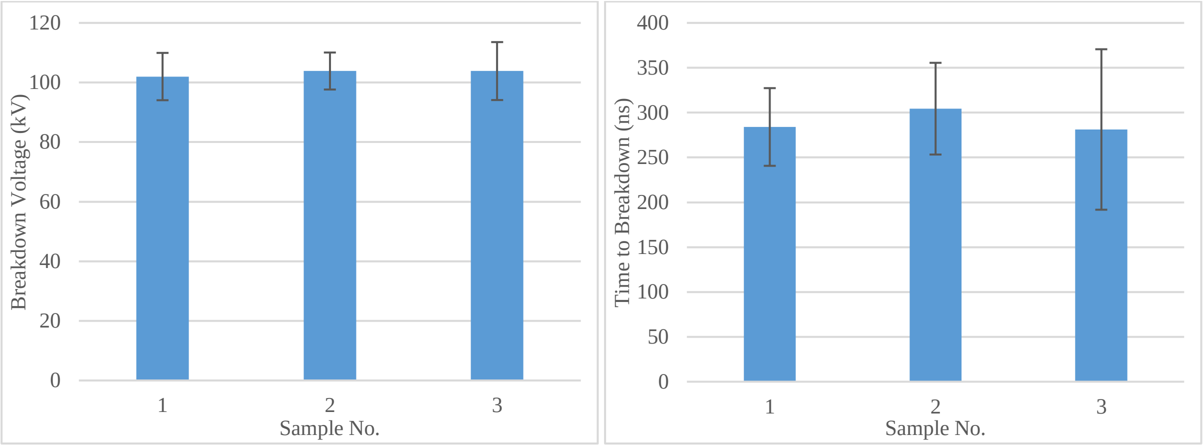
Figure 4-28; *Probability plots for 'Elevated humidity' mineral oil; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The conformance of the breakdown voltage data obtained when the mineral oil was subjected to negative lightning impulse was assured by the KS normality test (p-value 0.6). It is evident from the profile of the CPF (Figure 4-28a) that breakdown under negative lightning impulse predominately occurs at five levels of voltage; 140kV, 141kV, 142kV, 143kV and 144kV, which account for 23%, 17%, 13%, 20% and 13% of all breakdowns respectively. Despite the profile of the CPF, it is still possible to extract predicted values of breakdown voltage at the 10th, 50th and 95th percentiles; 140kV, 142kV and 145kV respectively.

The CPF produced from experimental time to breakdown data obtained under negative lightning impulse can be seen in Figure 4-28b. The data was subjected to the KS normality test and was shown to be normally distributed (p-value 0.61). Almost all (93%) of the data is seen to reside within the confidence bands, with the majority (80%) on, or close, to the distribution reference line. Despite the large majority of the data being placed on the distribution line there exists no data points at the upper and lower percentiles of interest. It is still possible however for extraction of the times which correspond to a 10%, 50% and 95% probability of breakdown; predicted to be 911ns, 1123ns and 1395ns respectively.

4.2.3.2. Breakdown of synthetic ester in the ‘Elevated humidity’ condition

Evaluation of the bulk liquid breakdown data obtained during the testing of the ‘Elevated humidity’ synthetic ester samples under lightning impulse showed that no upward or downward trend existed in the breakdown voltage or time to breakdown of the three liquid samples for either polarity of energising impulse. The lack of any clear trend in the experimental data allowed for the grouping of the ten separate breakdowns experienced by each sample into three discrete datasets for the purpose of mean value analysis.

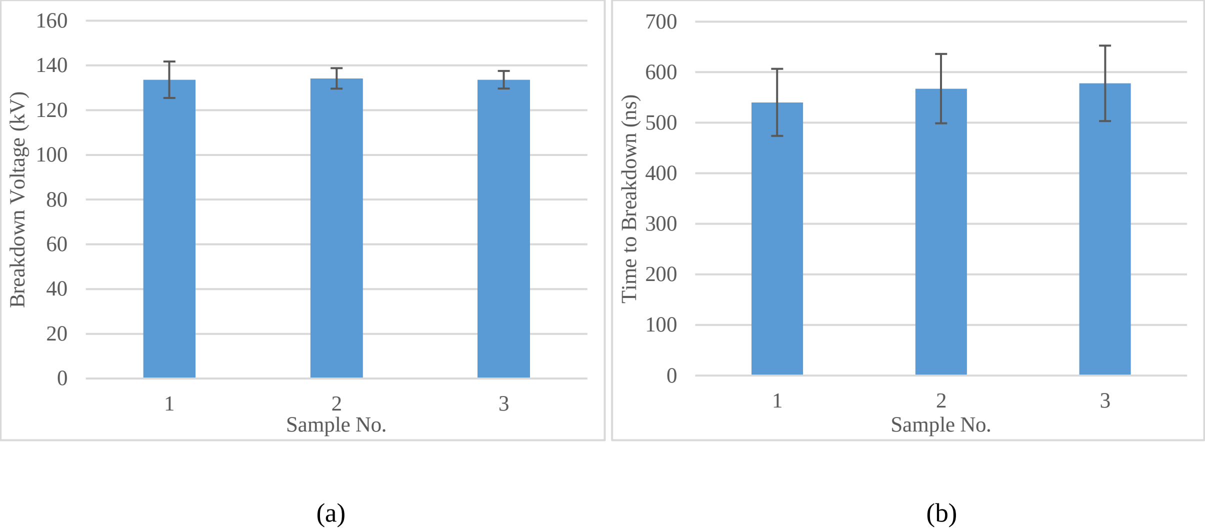


(a) (b)

Figure 4-29; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When the average breakdown voltage calculated for each of the three synthetic ester samples was examined it can be assumed that, due to the overlapping of confidence intervals, statistical difference may not be present between samples. There is however a small (2%) difference observed between the highest (104kV) and lowest (102kV) average breakdown voltage values, calculated for Sample 2 and Sample 1 respectively. Although given the overlapping of the 95% confidence error bars the samples can be thought of as exhibiting a statistically similar breakdown voltage and thus the grouping of the sample data into a larger dataset is possible. This new dataset (n = 30) was then used for CPF analysis.

The average time to breakdown of the three synthetic ester samples when in the ‘Elevated humidity’ condition under positive lightning impulse can be seen in Figure 4-29b. As with the data calculated for the average breakdown voltage, there is a likelihood of statistical similarity in the time to breakdown calculated for each of the three liquid samples. However, unlike the data shown in Figure 4-29a, the lowest calculated average time to breakdown (281ns) does not relate to Sample 1, rather Sample 3. This can be explained by the much larger error bars calculated for Sample 3 which indicate that the data is spread over a wide range of values which will include outliers that have clearly affected the average value. The highest average time to breakdown was, as with breakdown voltage, calculated for Sample 2 (304ns). As aforementioned, as there is a likely absence of statistical difference in the calculated sample averages, the grouping of the data into one single dataset is possible.



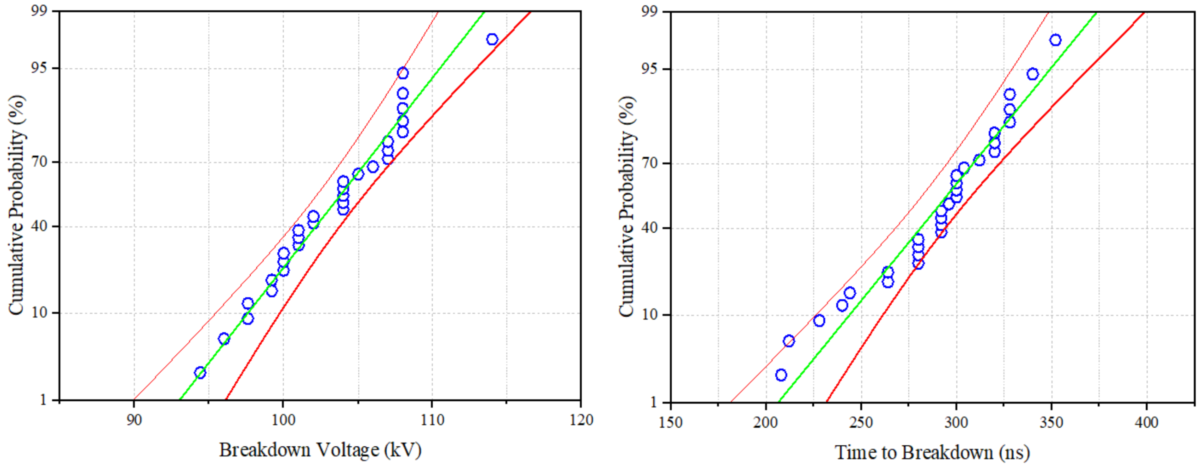
(a)

(b)

Figure 4-30; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The calculated average values of breakdown voltage for each of the three synthetic ester samples when under negative lightning impulse stress have been given in Figure 4-30a. It can be assumed from the data above that breakdown of the three sample is likely to occur at a statistically similar level of voltage. It is clear from both the closeness of the calculated average values of breakdown voltage as well as the overlapping confidence interval error bars that the pooling of the individual sample averages is possible; which will allow CPF analysis to be performed on the data.

The average values of time to breakdown calculated from the data gathered during the testing of the synthetic ester samples under negative lightning impulse can be seen in Figure 4-30b. As with breakdown voltage, all three liquid samples exhibit a likely absence of statistical difference in average time to breakdown at the selected degree of confidence. There is however, a 7% difference between the longest (578ns) and shortest (540ns) average values of this parameter; calculated for Sample 3 and Sample 1 respectively. This represents a much larger difference than is seen in the average values of breakdown voltage (7% as compared with 1%). This greater difference can be attributed to a larger spread in the time to breakdown data as compared with that of the breakdown voltage; supported by the presence of much larger error bars in the time to breakdown data. Furthermore, the longest average time to breakdown occurs in a different sample to that of the highest breakdown voltage; again, this is due to the larger spread of the time to breakdown data.



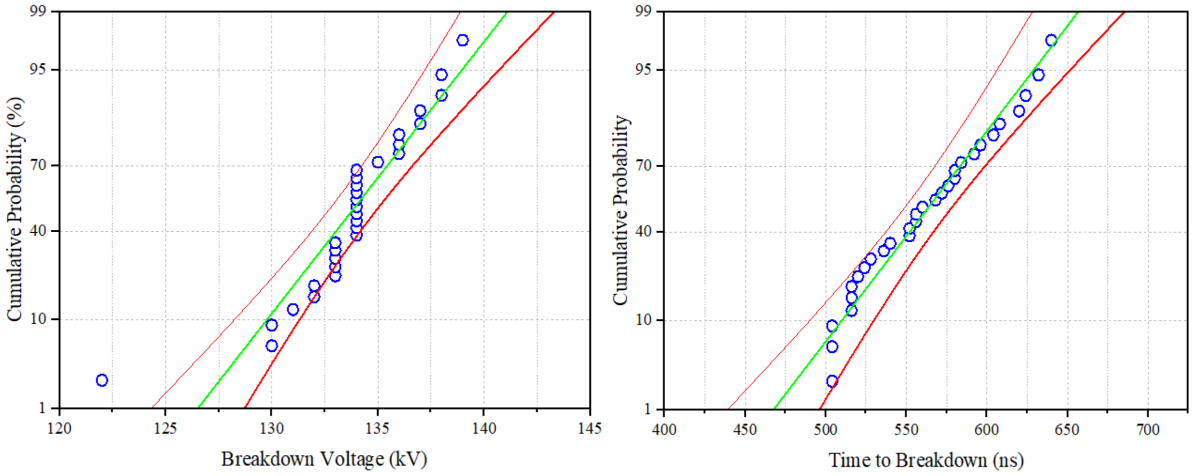
(a)

(b)

Figure 4-31; *Probability plots for 'Elevated humidity' synthetic ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data gathered during the testing of the synthetic ester under positive lightning impulse, CPF shown in Figure 4-31a, was confirmed by the KS normality test to be distributed normally (p-value 0.95). Study of the CPF shows that breakdown of the synthetic ester predominantly occurred at either 104kV or 108kV, each accounting for ~17% of all breakdowns. That said the CPF shows that multiple breakdowns also occurred at voltages between 98kV and 102kV as well as at 107kV. While the majority of the data is in good agreement with the distribution reference line, deviation from this line is observed in the upper percentile range. The predicted values of breakdown voltage for the synthetic ester at the 10th, 50th and 95th percentiles are; 98kV, 103kV and 110kV respectively.

The CPF produced from the time breakdown data obtained from stressing the synthetic ester with positive impulse can be seen in Figure 4-31b. The data can be said to be distributed normally, confirmed by the KS normality test (p-value 0.66). As with the breakdown voltage of the synthetic ester, the CPF shows that multiple breakdowns required the same time to breakdown. As a large amount (77%) of the data resides on the distribution reference line the extraction of the predicted time to breakdown at all percentiles of interest is possible; shown to be 244ns (10th), 290ns (50th) and 349ns (95th).



(a) (b)

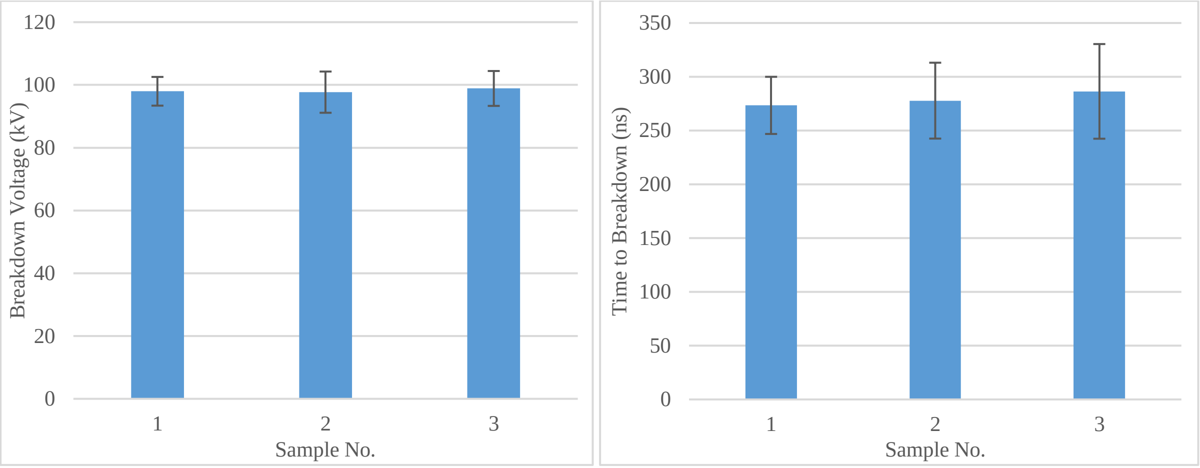
Figure 4-32; Probability plots for 'Elevated humidity' synthetic ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.

The normal distribution of the breakdown voltage data gathered during the testing of the synthetic ester under negative lightning impulse was confirmed by the KS normality test (p-value 0.16). It is clear from the CPF, shown in Figure 4-32a, that breakdown occurred predominately at two levels of voltage; either 133kV (17% of all breakdowns) or 134kV (~33% of all recorded breakdowns). Despite ~50% of all breakdowns occurring at these two levels of voltage, it is still possible to extract the predicted breakdown voltages at all percentiles of interest. From the CPF it is shown that breakdown voltage at the 10th, 50th and 95th percentiles are predicted to be 130kV, 134kV and 139kV respectively.

The time to breakdown data obtained during negative impulse testing of the synthetic ester is also normally distributed (p-value ~1). As is evident from evaluation of the CPF (Figure 4-32b) the data is in excellent agreement with the distribution reference line with 97% of the data residing on, or close, to this line. Predicted values of time to breakdown taken from the CPF at all percentiles of interest were 510ns (10th), 562ns (50th) and 629ns (95th).

4.2.3.3. Breakdown of natural ester in the 'Elevated humidity' condition

The breakdown voltage and time to breakdown of the natural ester samples in the 'Elevated humidity' condition under both positive and negative lightning impulse show no discernible trend in either of these breakdown parameters for any of the tested samples; with both increases and decreases in both breakdown parameters observed across the dataset of each sample. Thus, the decision was taken to group each set of 10 shots into three discrete datasets, one for per liquid sample, to allow for mean value analysis of both breakdown voltage and time to breakdown.

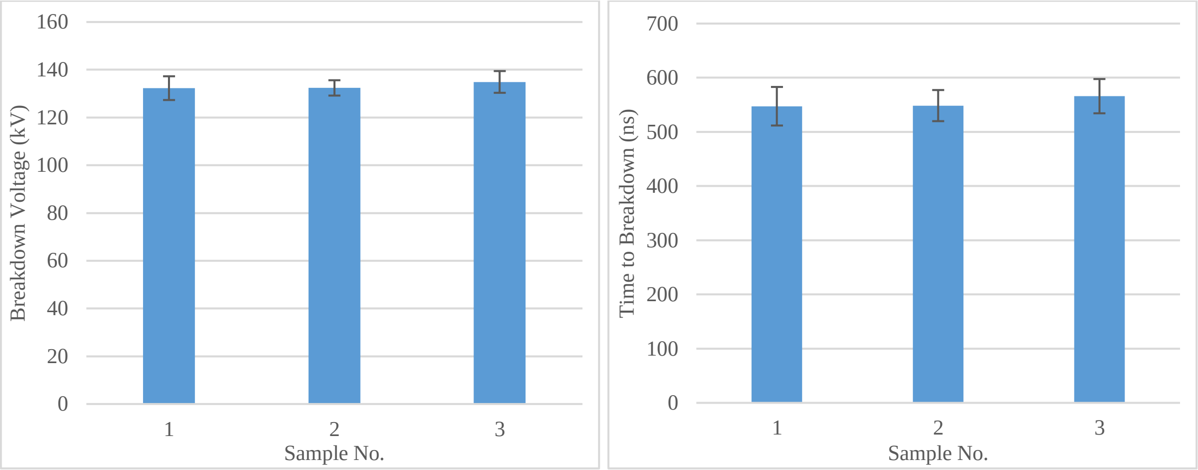


(a) (b)

Figure 4-33; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the natural ester samples when stressed with positive lightning impulse can be seen above (Figure 4-33a). It is evident from the data that breakdown of all liquid samples is likely to occur at a statistically similar level of breakdown voltage, given the overlap in the 95% confidence intervals. Given the small variation in the average breakdown voltage seen between samples it is unsurprising that the calculated error bars overlap in all cases. Consequently the decision was made to group the data taken for each sample to produce one large dataset (n = 30) to facilitate CPF analysis.

The average time to breakdown calculated for each of the natural ester samples show identical behaviour to that of the breakdown voltage; with Sample 3 requiring the longest average time to breakdown (286ns) and Sample 1 the shortest (273ns). This represents a difference of ~4%, which is higher than exists between the breakdown voltages of the aforementioned samples (~1%). This discrepancy can be attributed to the individual values of time to breakdown which make up the discrete datasets of each sample being spread over a wider range of values; confirmed by the larger error bars associated with this data. Given the larger size of the time to breakdown error bars it is unsurprising that this data also shows a likely lack of statistical difference between samples; where again data will be grouped for CPF analysis.

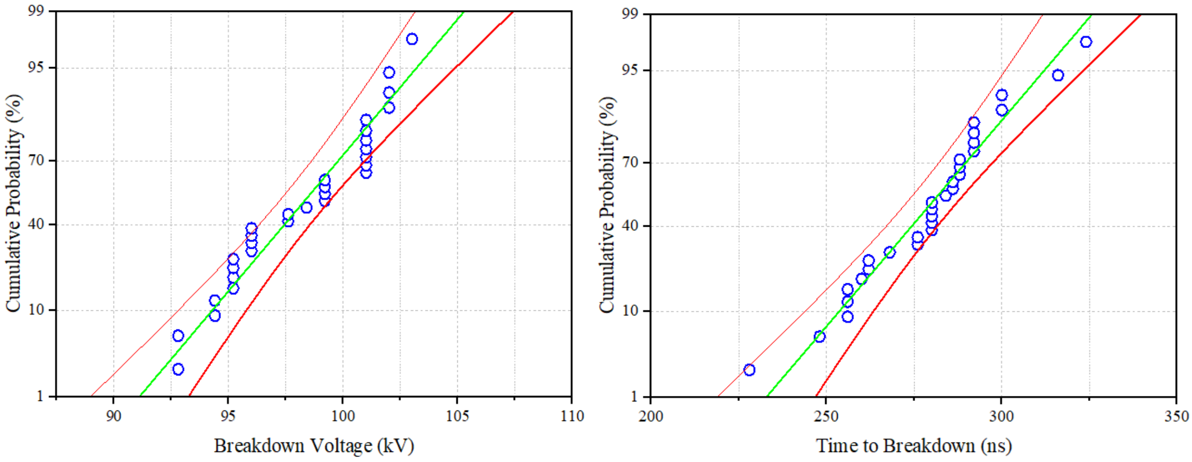


(a) (b)

Figure 4-34; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Figure 4-34a shows the calculated values of average breakdown voltage for each of the three natural ester samples when stressed with negative lightning impulse. From the aforementioned figure it is clear that all confidence intervals overlap and thus likely that the breakdown of all three liquid samples occurs at a similar level of voltage. The likely presence of statistical similarity in the average breakdown voltage of the three liquid samples allowed for the grouping of the data for means of CPF analysis.

The average time to breakdown of each of the three liquid samples can be seen in Figure 4-34b, where statistical difference at the selected degree of confidence may not exist between samples. As with the breakdown voltage data, the longest average time to breakdown is calculated for Sample 3 (566ns) with the lowest average value associated with Sample 1 (548ns). This represents a slightly larger difference than is seen in the average breakdown voltage data (3% as compared with 2%), however given the larger error bars in the time to breakdown data this can be attributed to a wider spread of the time to breakdown data affecting the calculated average values. Again, the overlapping error bars in the time to breakdown data facilitate the ability to group the data of each of the three samples into one single dataset for the purpose of CPF analysis.

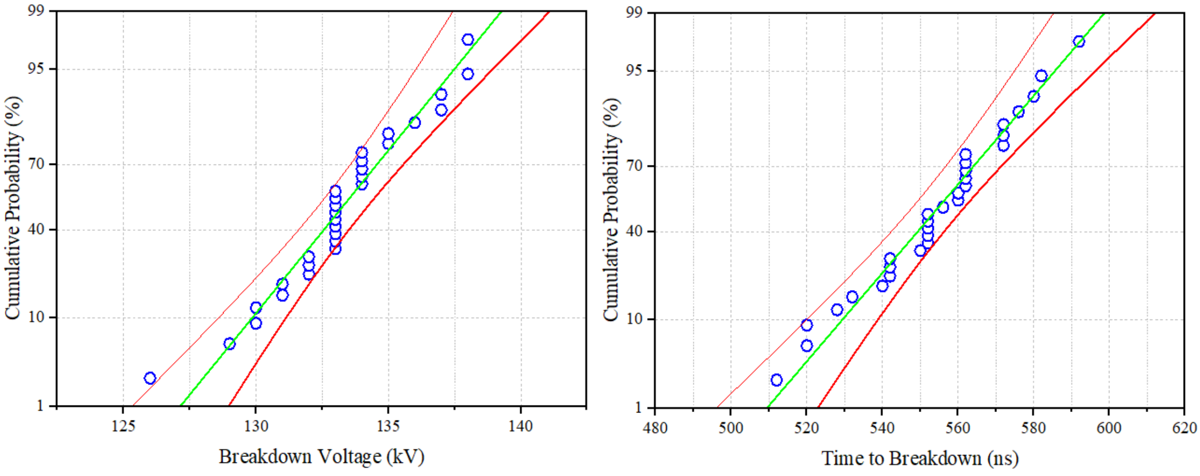


(a) (b)

Figure 4-35; *Probability plots for 'Elevated humidity' natural ester; CPFs for positive lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from the breakdown voltage data gathered during the testing of the natural ester samples under positive lightning impulse is shown in Figure 4-35a. The data was confirmed as being of normal distribution by the KS normality test (p-value 0.21). From the profile of the CPF, it is clear that breakdown predominately takes place at five discrete levels of voltage with multiple breakdowns seen at voltages between 95kV and 102kV. The most common level of voltage resulting in breakdown of the natural ester was 101kV, which accounted for ~23% of all breakdowns observed. Despite the placement of the experimental data points it is possible to extract the predicted levels of breakdown voltage at all percentiles of interest; these are shown to be 94kV ($V_{10\%}$), 98kV ($V_{50\%}$) and 103kV ($V_{95\%}$).

The data obtained relating to the time to breakdown of the natural ester under positive stress can be said to be distributed normally (p-value 0.48). As is the case with the breakdown voltage data, there are multiple breakdown events which required an identical time to breakdown; observed between 256ns and 292ns. Despite this it is possible to extract predicted values of the time to breakdown parameter at all percentiles of interest; corresponding to 254ns (10th), 279ns (50th) and 312ns (95th).



(a) (b)

Figure 4-36; *Probability plots for 'Elevated humidity' natural ester; CPFs for negative lightning impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained during the testing of the natural ester under negative lightning impulse can be said to be distributed normally after being subjected to the KS normality test (p-value 0.32). From review of the CPF, shown in Figure 4-36a, it is obvious that breakdown predominately occurs at two voltage levels; 133kV and 134kV which account for 30% and 17% of all breakdowns respectively. There are however other levels of voltage at which multiple breakdowns occur but none to the extent of the aforementioned values. Given that all but one of the experimental data points are contained within the confidence bands, with the majority residing on the distribution reference line, predicted values of breakdown voltage at all percentiles of interest is possible. The breakdown voltage values predicted by the distribution for the 10th, 50th and 95th percentiles are 130kV, 133kV and 138kV respectively.

The time to breakdown data (Figure 4-36b) is shown by the KS normality test to be distributed normally with a p-value of 0.72. The CPF clearly shows that a number of breakdowns occur with an identical time to breakdown, like breakdown voltage this occurs at two particular levels (552ns and 562ns) but interestingly for only 34% of the data rather than 47%. This can be explained due to breakdown occurring at a point at which the change in voltage is smaller than occurs in time to breakdown; allowing multiple time values to be associated with the same level of breakdown voltage. Despite this, the data still has a strong conformance with the normal distribution which allows for values at all percentiles of interest to be predicted by the CPF. These are shown to be 529ns (10th), 554ns (50th) and 586ns (95th).

4.2.3.4. Summary of breakdown of dielectric liquids in the 'Elevated humidity' condition

The chosen dielectric liquids in the 'Elevated humidity' condition were stressed with lightning impulses of both positive and negative polarity. Obtained experimental data for each of the three individual samples of the dielectric fluids was evaluated and it was shown that no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, existed; irrespective of energisation polarity. This allowed for the pooling of sample data into three discrete datasets for each of the three liquids which was then used in mean value analysis. Evaluation of this data demonstrated that statistical difference existing in the breakdown parameters of the three samples for a given liquid and impulse polarity was unlikely; facilitating the grouping of the three discrete datasets into a larger pool for the means of cumulative probability analysis. Calculated values of the breakdown parameters derived from both the mean and CPF analysis have been summarised in Table 4-3.

Table 4-3; *Average breakdown voltage and time to breakdown of 'Elevated humidity' dielectric fluids when stressed with lightning impulse.*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	122 ± 9.1kV	113kV	138kV	0.04
	MIDEL 7131	103 ± 7.5kV	98kV	110kV	0.95
	Envirotemp FR3	98 ± 5.2kV	94kV	103kV	0.21
Negative impulse	Shell Diala S4	142 ± 3.2kV	139kV	145kV	0.6
	MIDEL 7131	134 ± 5.3kV	130kV	139kV	0.16
	Envirotemp FR3	133 ± 4.2kV	130kV	138kV	0.32
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	419 ± 110ns	336ns	526ns	0.45
	MIDEL 7131	290 ± 61ns	244ns	349ns	0.66
	Envirotemp FR3	279 ± 34ns	254ns	312ns	0.48
Negative impulse	Shell Diala S4	1123 ± 281ns	911ns	1395ns	0.61
	MIDEL 7131	562 ± 69ns	510ns	629ns	~1
	Envirotemp FR3	552 ± 33ns	530ns	586ns	0.72

When examining the mean values of breakdown voltage when the 'Elevated humidity' dielectric liquids are subjected to positive lightning impulse it is apparent that breakdown of the mineral oil occurs at a statistically higher level of voltage than both ester fluids; which have been shown to likely require a statistically similar level of voltage to cause breakdown. Under negative impulse stress, again the mineral oil has a statistically higher breakdown voltage than that of the natural ester fluid, though not the synthetic ester which is shown to possess a statistically similar dielectric strength to that of the mineral oil. As was the case with positive energisation, both ester fluids require a statistically similar negative voltage to result in breakdown of the fluid.

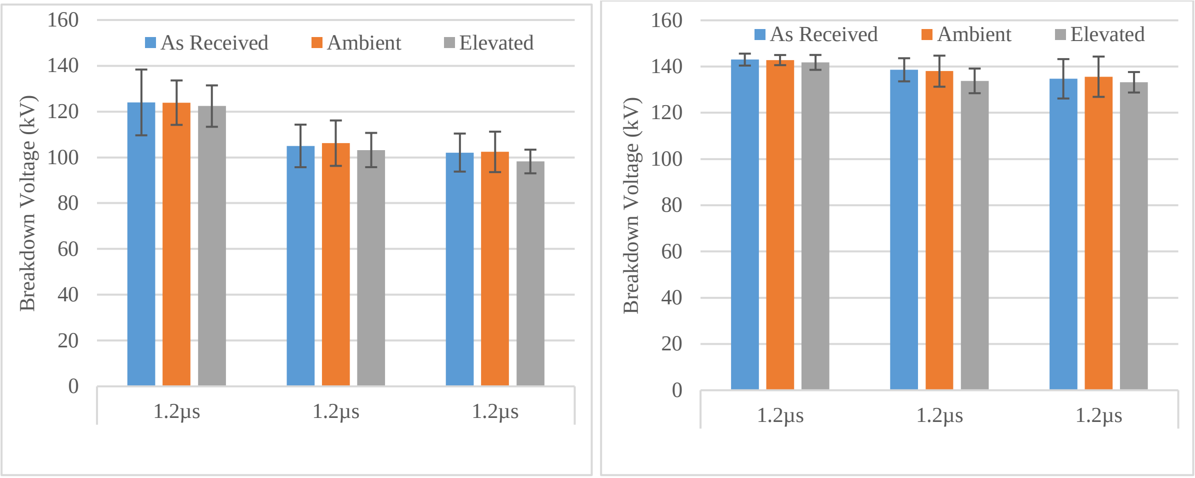
It has been shown that under positive lightning impulse all three dielectric fluids are likely to require a statistically similar time to breakdown. This is in contrast to what is observed in the breakdown voltage data and is as a result of the wide spread of values contained within the mineral oil dataset. When the energising impulse is of negative polarity the time to breakdown again contradicts the observations made in the breakdown voltage data; with the mineral oil now seen to require a statistically longer time to breakdown than both ester liquids not just the natural ester. This can be attributed to the breakdown of the mineral oil taking place on or close to the plateau of the energising impulse when a large change in time to breakdown corresponds to a small change in breakdown voltage. For both ester fluids it was again shown that statistical difference in the time necessary to result in breakdown may not exist at the selected degree of confidence.

Evaluation of the predicted values of breakdown voltage for the liquids when under positive impulse show that while both ester fluids share similar levels of predicted breakdown voltage those expected for the mineral oil are significantly higher (between 17% and 25%) at all percentiles of interest. Further to this breakdown of the mineral oil is predicted to occur over a wider range of values than both ester fluids; demonstrating a greater variability in dielectric behaviour than the chosen ester fluids. Both ester fluids are shown to have similar breakdown behaviour under positive impulse with only a ~5% difference in predicted values of breakdown voltage at all percentiles of interest; with the synthetic ester possessing the greater dielectric strength. When under negative impulse stress again the mineral oil is seen to have the highest dielectric strength at all percentiles of interest; ~7% greater than that of both ester fluids. Similar to when under positive stress only a small (1kV) difference exists in the predicted values of voltage required to cause breakdown of the ester fluids; with both fluids predicted to require the same level of breakdown voltage at the lowest percentile of interest (10th). In contrast to the predicted values of breakdown voltage under positive impulse, when under negative stress breakdown of the mineral oil is now predicted to occur over a narrow range of values; which is a consequence of breakdown occurring near the peak of the voltage impulse where little change in voltage is observed.

The values of time to breakdown predicted by the CPF analysis of each of the dielectric liquids have also been given in Table 4-3. Under positive lightning impulse, the mineral oil requires a longer time to breakdown than both ester liquids at all percentiles of interest. As with the predicted values of breakdown voltage, the time to breakdown of the mineral oil can be seen to be spread over a wider range of values than that of the ester liquids. Both ester fluids require a similar time to breakdown with only a 4% difference in this parameter at the lower and middle (10th and 50th) percentiles but increasing to ~11% at the higher percentile (95th). Interestingly the predicted time to breakdown of the synthetic ester is seen to be higher than that of the natural ester at both the 50th and 95th percentiles but lower at the 10th. This can be attributed to the greater spread of the time to breakdown data for testing involving the synthetic ester; confirmed with the larger confidence intervals linked to this data. When the impulse is of negative polarity, again the mineral oil requires a significantly longer time to breakdown than both ester fluids; at times in excess of twice as long (95th percentile). Again, the time to breakdown of the mineral oil is spread over a wider range of values than the ester fluids; attributed to the much higher dielectric strength of this fluid. Both the synthetic and natural ester again exhibit similar performance, with only between 2% and 7% difference in predicted time to breakdown of the two liquids.

4.3. Summary of breakdown under lightning impulse

This chapter has presented the results of experiments conducted involving the three chosen dielectric liquids (Shell Diala S4 mineral oil, MIDEL 7131 synthetic ester and Envirotemp FR3 natural ester) in three discrete states of relative humidity (‘As Received’, ‘Ambient humidity’ and ‘Elevated humidity’). Three samples of each of the chosen liquids in the given states of relative humidity were stressed with lightning impulses of both positive and negative polarity. The samples were exposed to ten separate breakdown events with breakdown voltage and time to breakdown recorded. This data was then subjected to both mean value and cumulative probability analysis.



(a) (b)

Figure 4-37; *(a) Positive and (b) negative lightning impulse breakdown voltage of the mineral oil, synthetic ester and natural ester in the three discrete levels of relative humidity. Each column is the mean of thirty individual breakdown events, with error bars showing 95% confidence intervals.*

The data provided on the mean breakdown voltage of the three dielectric liquids when stressed with positive lightning impulse (Figure 4-37a) has shown that in all cases the mineral oil has a higher dielectric strength than both the synthetic and natural esters. In the ‘As Received’ condition breakdown is seen to occur at a statistically similar level of voltage for all three fluids; however, this is not the case when comparing the mineral oil and natural ester at the higher levels of relative humidity. There is a clear, statistically significant, difference in the breakdown voltage of the mineral oil and natural ester at both the ‘Ambient’ and ‘Elevated’ humidity levels. This is also the case when comparing the mineral oil and synthetic ester at the highest level of relative humidity. These observations cannot be attributed to the absolute water content of the fluid, as it is clear from Figure 4-37a that for a given dielectric liquid the level of relative humidity has no effect on the average level of breakdown voltage, with breakdown seen to occur at a similar level irrespective of the relative humidity of the fluid given the overlapping of the confidence intervals in all cases. This is not surprising given the negligible effect fluid condition has over short duration (< tens of microseconds) impulse breakdown. It has been shown in [16], [82] that breakdown of dielectric liquid under such impulse voltages is governed by the intrinsic properties of the liquid rather than the condition of the fluid. This can be attributed to breakdown occurring as a result of streamer development in the fluid which is determined by the ionisation properties of the fluid and is much less sensitive to the presence of contaminants than if a process of electrostriction (bubble formation) was the main breakdown mechanism; which is the case in AC breakdown where voltages are applied for tens of microseconds before breakdown. That said breakdown under impulse voltage is sensitive to experimental conditions [18], however this is not thought to be a factor in the observations made in this thesis given that liquids were tested under identical experimental conditions and the same defined testing methodology was used throughout all experimentation.

The breakdown voltages of the chosen dielectric liquids under negative lightning impulse stress are depicted in Figure 4-37b. It is evident from the data presented in Figure 4-37b that breakdown occurs at a statistically similar level of breakdown voltage for all three fluids at both the ‘As Received’ and ‘Ambient’ humidity levels as well as the mineral oil and synthetic ester in the ‘Elevated humidity’ condition. The only significant difference in breakdown voltage is observed when comparing the breakdown of the mineral oil and natural ester in the ‘Elevated humidity’ condition. Both ester fluids are shown to breakdown at a statistically similar level of voltage irrespective of the level of relative humidity. Again, there is no notable effect on the breakdown voltage of a given fluid when the relative humidity is increased; demonstrated by the likely lack of a statistical difference in breakdown voltage when humidity is heightened. The absence of any effect in the observed breakdown voltage when humidity is increased is, as previously mentioned, not surprising given the resilience of impulse breakdown voltage to changes in fluid condition.

It can be said that breakdown of each of the three dielectric liquids always occurs at a higher level of voltage when the impulse is of negative polarity. Interestingly though the breakdown voltages of the three fluids under negative impulse are much closer to each other than when the impulse is of positive polarity. When examining the highest and lowest average breakdown voltages, which in both cases occur for the mineral oil (highest) and natural ester (lowest) in the ‘Elevated humidity’ condition, there exists only a 7% difference in calculated averages when the impulse is negative but a 20% difference when under positive voltage stress. This small difference in negative breakdown voltage can be, partially attributed to breakdown of the fluids occurring near the peak output voltage of the impulse circuit. Were the nominal peak amplitude of the impulse to be increased it is believed that a larger disparity in breakdown strength would exist between the mineral oil and ester fluids.

Table 4-4; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under positive lightning impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	423 ± 123ns	18.9km/s	26.7km/s	14.7km/s	3rd
	MIDEL 7131	294 ± 71ns	27.2km/s	35.9km/s	21.9km/s	3rd
	Envirotemp FR3	287 ± 40ns	27.9km/s	32.4km/s	24.5km/s	3rd
Ambient humidity	Shell Diala S4	423 ± 104ns	18.9km/s	25.1km/s	15.2km/s	3rd
	MIDEL 7131	297 ± 60ns	26.9km/s	33.8km/s	22.4km/s	3rd
	Envirotemp FR3	287 ± 66ns	27.9km/s	36.2km/s	22.7km/s	3rd
Elevated humidity	Shell Diala S4	419 ± 110ns	19.1km/s	25.9km/s	15.1km/s	3rd
	MIDEL 7131	290 ± 61ns	27.6km/s	34.9km/s	22.8km/s	3rd
	Envirotemp FR3	279 ± 34ns	28.7km/s	32.7km/s	25.6km/s	3rd

Table 4-5; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under negative lightning impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	1255 ± 357ns	6.4km/s	8.9km/s	4.9km/s	2nd/3rd
	MIDEL 7131	588 ± 52ns	13.6km/s	14.9km/s	12.5km/s	3rd
	Envirotemp FR3	557 ± 134ns	14.4km/s	18.1km/s	11.6km/s	3rd
Ambient humidity	Shell Diala S4	1188 ± 179ns	6.7km/s	7.9km/s	5.9km/s	2nd/3rd
	MIDEL 7131	585 ± 75ns	13.7km/s	15.7km/s	12.1km/s	3rd
	Envirotemp FR3	599 ± 133ns	13.4km/s	17.2km/s	10.9km/s	3rd
Elevated humidity	Shell Diala S4	1123 ± 281ns	7.1km/s	9.5km/s	5.7km/s	2nd/3rd
	MIDEL 7131	562 ± 69ns	14.2km/s	16.2km/s	12.7km/s	3rd
	Envirotemp FR3	552 ± 33ns	14.5km/s	15.4km/s	13.7km/s	3rd

Table 4-4 shows the average time to breakdown of the three dielectric liquids in each state of relative humidity when under positive lightning impulse stress. The table also shows the minimum average propagation velocity of breakdown streamers (calculated by dividing the inter-electrode gap distance by the average time to breakdown) and the upper and lower calculated velocities which are derived from the upper and lower average time to breakdown values. As no account has been taken of the statistical time (time for onset of the streamer), the velocities stated herein can be thought of as the minimum average velocities at which the streamer propagates through the gap. From Table 4-4 it can be seen that under positive voltage stress statistical difference in average time to breakdown for a given liquid may not exists at the selected degree of confidence as the relative humidity of the fluid is increased. Likewise, statistical difference may not exist between liquids at any of the investigated humidity levels. Consequently, it is unsurprising that all liquids exhibit the development of similar, namely 3rd mode, streamer velocities. It can be said that at all levels of relative humidity streamers in mineral oil propagate slower than those in both the synthetic ester and natural ester fluids; with streamers in these liquids seen to move at very similar velocities. This is of no great surprise given the well documented inability of ester fluids to hold off streamer acceleration and the much lower acceleration voltages observed for these liquids compared to mineral oil [13], [15], [68].

Evaluation of the average time to breakdown data gathered from stressing the fluids with negative lightning impulse, presented in Table 4-5, shows that at all levels of relative humidity the mineral oil requires a statistically longer average time to breakdown than both ester fluids. Again, both the natural and synthetic ester fluids breakdown after a statistically similar time. Relative humidity of the fluid is, as with positive breakdown, shown to exert a negligible influence on breakdown performance of the liquids with statistical difference likely not be present in the time to breakdown of a given dielectric liquid as relative humidity is increase from the lowest to highest examined levels. Streamer velocity under negative energisation is shown to be lower for each of the dielectric liquids than when under positive voltage stress, this is to be expected given the ionisation mechanism which drives streamer propagation under negative voltage. Given their bush-like nature, as well as the development of negative space charge in the region of the streamer that resists growth, negative streamers propagate at a much slower rate than positive counterparts [15]. That said, both the natural and synthetic ester fluid are still seen to harbour 3rd mode streamers, though at much lower propagation velocities than when the liquids are under positive voltage stress (~14km/s as compared with ~30km/s). The streamers developed in the mineral oil under negative lightning impulse are shown to propagate at the slowest velocities observed during experimentation. Velocities of <10km/s are calculated for streamers in the mineral oil at all states of relative humidity; with some shown to propagate as slow as <5km/s. This corresponds to the transition between 2nd and 3rd modes which is to be expected given the much higher voltages required to transition a streamer to the 'faster' modes within mineral oil [15].

To conclude the work discussed in this chapter, it has been shown that under positive lightning impulse voltage natural and synthetic ester fluids exhibit levels of breakdown voltage and time to breakdown likely to be statistically similar to that of mineral oil; with similar streamers developed in all three liquids. However, when under negative lightning impulse stress while the two ester fluids still exhibit a statistically similar performance in terms of their breakdown voltage and time to breakdown the mineral oil is shown to offer statistically better (higher) breakdown performance for both breakdown voltage and time to breakdown. Streamers developed in the liquids are also different under negative energisation with clearly 3rd mode streamers generated in the ester fluids but those transitioning from 2nd to 3rd mode observed in the mineral oil. It can also be said that irrespective of energisation polarity the relative humidity of the fluid has no influence on either the breakdown voltage or time to breakdown of the examined mineral oil or ester fluids.

Chapter 5 – Breakdown of insulating fluids with impulses of 7µs rise-time

5.1. Introduction

In order to ascertain the effect the rise-time of the impulse has on the observed breakdown behaviour of the chosen ester fluids and how this compares to conventional mineral oil experiments were conducted during which the fluids were stressed with a much longer impulse than the standard lightning impulse: 7µs rise-time as compared with the 1.2µs used in the work discussed in Chapter 4. The proceeding chapter is concerned with the presentation and discussion of experimental results gathered from breakdown tests conducted under 7µs impulse stress. As with the work discussed in the previous chapter the effect of impulse polarity was also investigated, with liquids stressed with impulses of both positive and negative polarity. The chosen liquids were tested in accordance with the testing methodology described in Section 3.6.1. Within this chapter the breakdown voltage and time to breakdown for each of the ten individual breakdowns of a single liquid sample, as well as the mean of these values, is presented along with the cumulative probability function for the entire dataset gathered for a given dielectric liquid. Firstly, experimental data will be presented and evaluated for similarity between the breakdown of individual liquid samples of a given dielectric fluid and relative humidity. Analysis of the mechanisms that may be responsible for the behaviours observed will be presented and discussed within the summary (Section 5.3) at the end of the chapter.

5.2. Experimental results

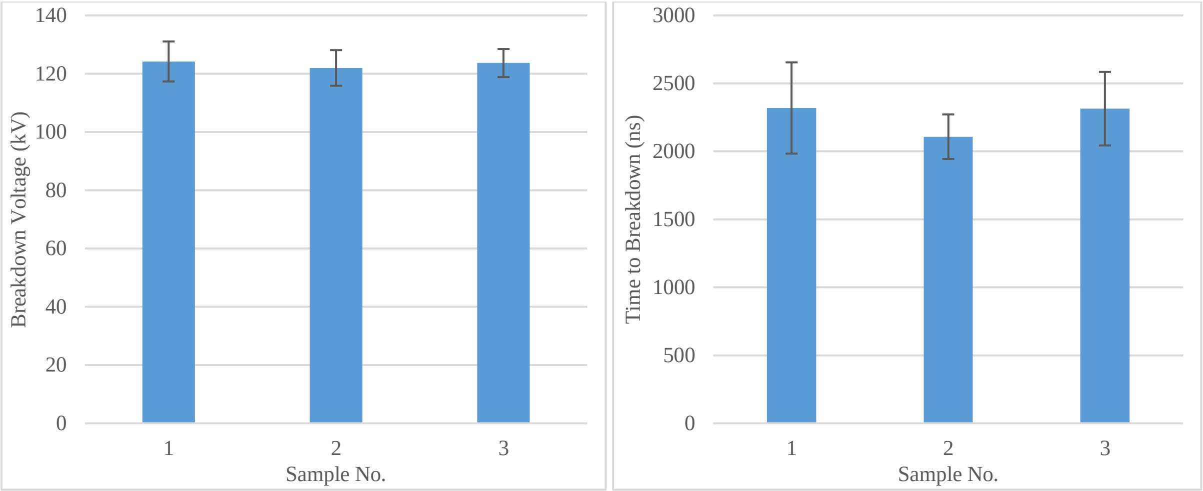
This section, and associated subsections, detail the experimental results obtained from stressing the liquid samples with impulses considerably longer, hence forth to be referred to as the ‘Microsecond’ impulse, than that of the lightning impulse discussed in the previous chapter (rise-time of 7µs compared with 1.2µs for the standard lightning impulse). The effect voltage polarity may exert on the breakdown performance of the fluids was also evaluated with the use of both positive and negative impulses. The gathered experimental data has been subdivided into groupings based on the three discrete levels of relative humidity of each liquid sample; discussed in detail in Section 3.3.1.

5.2.1. Breakdown of liquid in ‘As Received’ condition

Data presented in this section pertains to the breakdown of liquid samples in the condition as provided by the manufacturer. The only conditioning of the liquid samples was that of degassing prior to the commencement of any breakdown tests; as discussing in Section 3.6.1. The relative humidity of liquid samples in the ‘As Received’ condition was 21%, 12.5% and 9% for the mineral oil, synthetic ester and natural ester respectively.

5.2.1.1. Breakdown of mineral oil in ‘As Received’ condition

The breakdown voltage and associated time to breakdown of the mineral oil samples in the ‘As Received’ condition (~21% relative humidity) will be presented in this section. Review of the ten individual breakdown events of each of the liquid samples has shown that, irrespective of energisation polarity, there exists no clear degradation, or increase, to the breakdown strength of a given liquid sample as the shot number is increased; i.e. there is no clear reduction in breakdown voltage, or time to breakdown, when comparing the first and last (10th) breakdown in the test series. It is therefore allowable that the ten discrete breakdown events for a given sample can be grouped into a single dataset to facilitate mean value analysis.

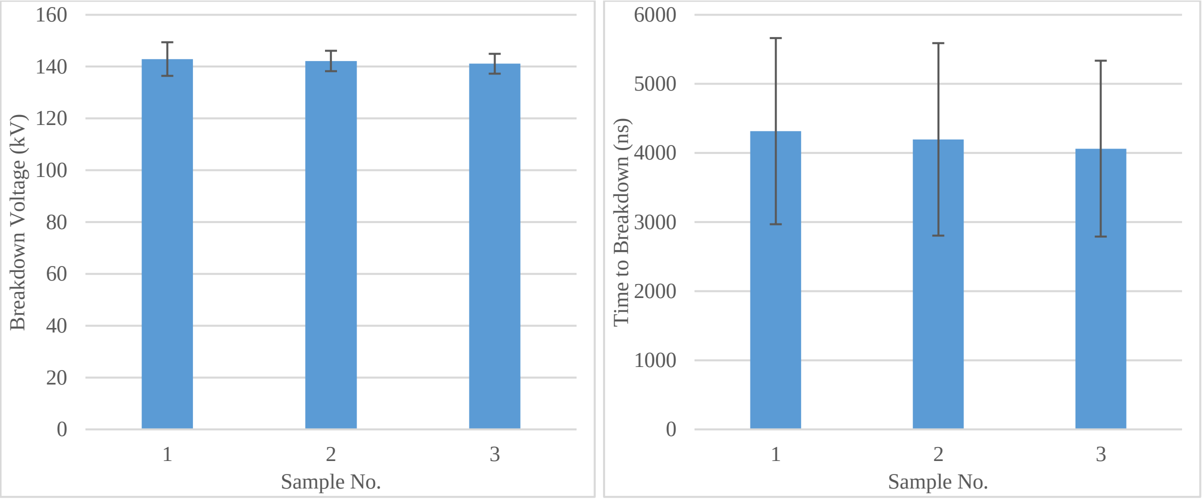


(a) (b)

Figure 5-1; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

From the data presented in Figure 5-1a it can be said that breakdown of the three samples is likely to occur at a similar level of voltage given the overlap in the 95% confidence intervals. It is clear from both the closeness of the calculated average values of breakdown voltage as well as the overlapping 95% confidence intervals that the pooling of the sample averages is possible allowing CPF analysis to be performed on the data.

The average time to breakdown of each of the three mineral oil samples can be seen in Figure 5-1b, where no statistical difference may exist in the calculated averages of each sample at the selected degree of confidence. As with the breakdown voltage data, the longest average time to breakdown is calculated for Sample 1 (2319ns) with the lowest average values associated with Sample 2 (2110ns). This represents an increase in the difference that exits between average breakdown voltages calculated for each liquid sample data (9% as compared with 2%). This can be attributed to the larger spread of the experimental data for the time breakdown parameter, as compared with that of breakdown voltage. Given the probable lack of statistical difference in the calculated average values of time to breakdown it is reasonable to pool this data and for it to be used in CPF analysis.

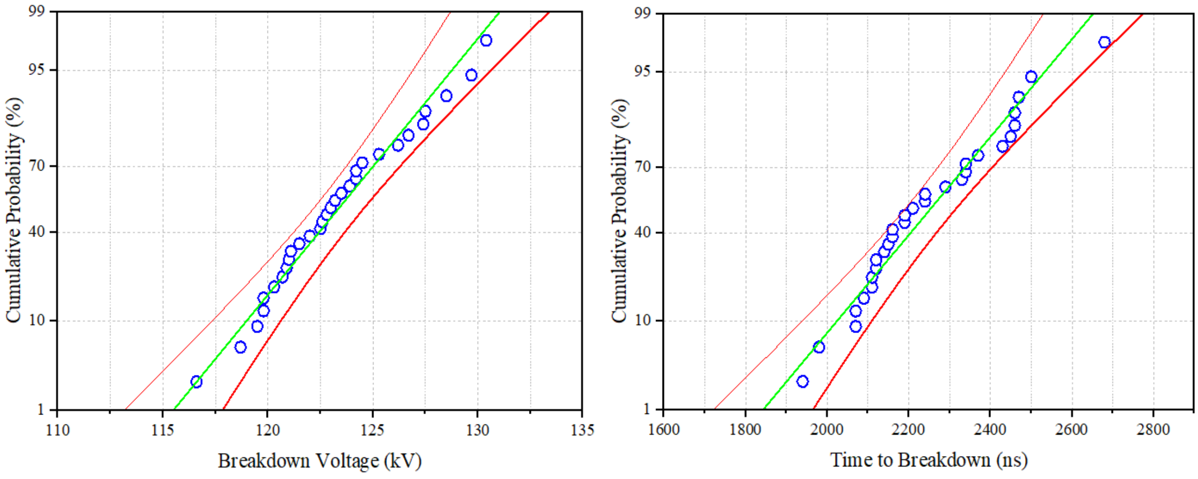


(a) (b)

Figure 5-2; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The data gathered during the testing of the mineral oil samples in the ‘As Received’ conditions under negative microsecond impulse shows that statistical difference may not be present in the breakdown voltage of each of the three individual liquid samples (Figure 5-2a). Due to overlapping of the 95% confidence intervals grouping of the three sample datasets into a larger single dataset is possible with this to be used for cumulative probability analysis.

The average time to breakdown of the three individual mineral oil samples (Figure 5-2b) again shows possible lack of statistical variation between samples. There is again a larger sample-to-sample difference in calculated average values of time to breakdown than that of the breakdown voltage (~6% in the time to breakdown values as compared with ~1% in breakdown voltage). This discrepancy results from a greater spread of the time to breakdown data, which is supported by the much larger error bars associated with this data as compared with that of the breakdown voltage. As all error bars overlap for the data it is reasonable to pool the data of each sample into one large dataset for CPF analysis.



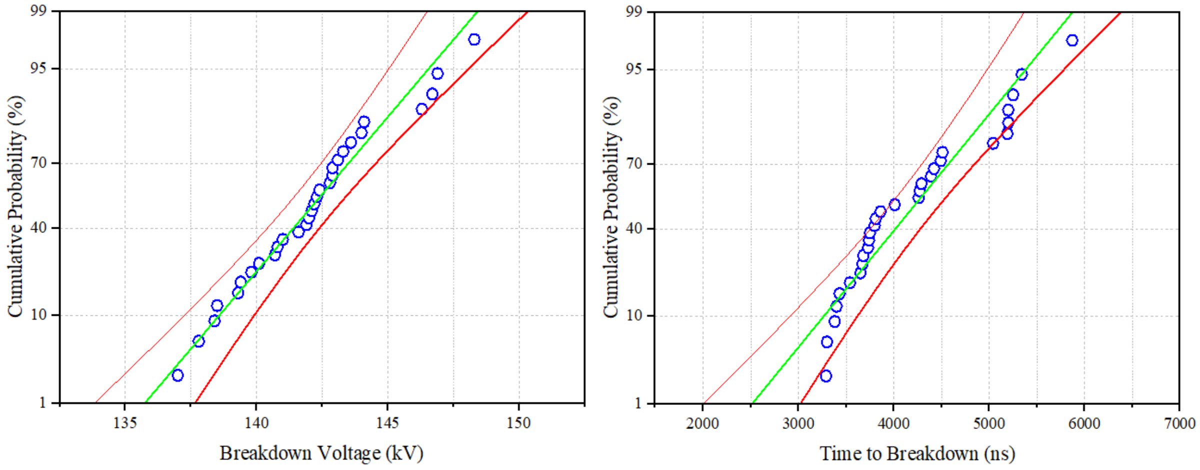
(a) (b)

Figure 5-3; *Probability plots for 'As Received' mineral oil; CPFs for positive 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The distribution of the breakdown voltage data gathered during the stressing of the ‘As Received’ condition mineral oil with the positive polarity microsecond impulse was shown to be normal by means of the KS normality test (p-value ~1). As can be seen in Figure 5-3a the experimental data is in excellent agreement with the predicted distribution reference line, with almost all data points residing on this line.

From the aforementioned distribution the predicted levels of breakdown voltage at the percentiles of interest (10th, 50th and 95th) can be extracted; shown to be 119kV, 123kV and 129kV respectively.

The CPF produced from the time to breakdown data obtained during the testing of the mineral oil under positive microsecond impulse has been given in Figure 5-3b. The data set is of normal distribution as the KS normality test performed on the dataset delivered a p-value of ~0.69. All experimental data points reside within the confidence bands, with the vast majority sitting on the distribution reference line. The predicted time to breakdown is 2025ns, 2247ns and 2533ns for $t_{10\%}$, $t_{50\%}$ and $t_{95\%}$ respectively.



(a) (b)

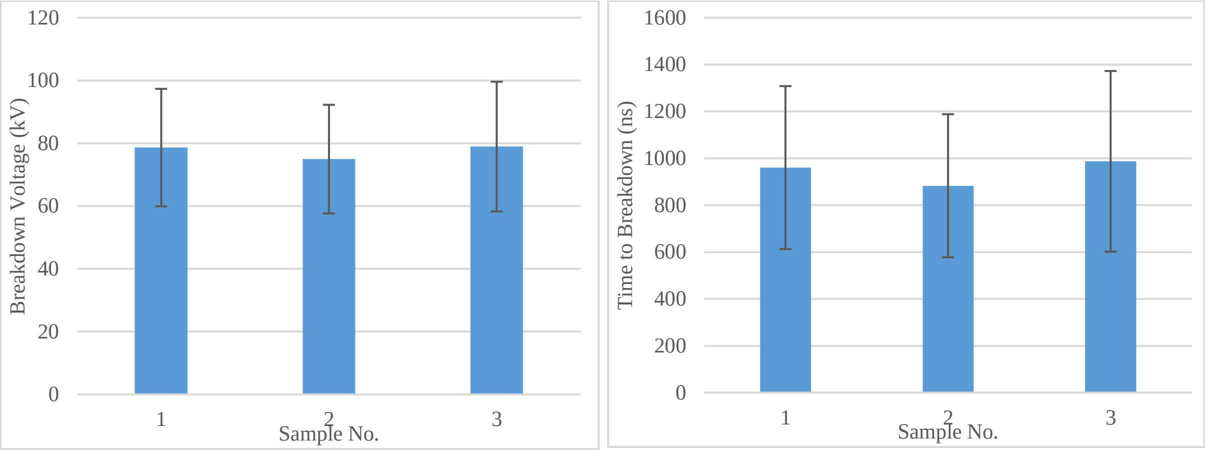
Figure 5-4; *Probability plots for 'As Received' mineral oil; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The experimental data gathered when the samples of ‘As Received’ condition mineral oil were stressed with microsecond impulses of negative polarity is again distributed normally (KS p-value ~1). As is evident from the CPF shown in Figure 5-4a, all experimental data points are contained within the upper and lower confidence banding with all but those in the 80-90th percentile region sitting on the distribution reference. Given the data conforms to the normal distribution the breakdown voltages for the 10th, 50th and 95th percentiles can be extracted from the CPF; 139kV, 142kV and 147kV respectively.

The time to breakdown of each of the mineral oil samples under negative microsecond impulse stress is also shown to be distributed normally, with a p-value of ~0.27. Unlike the CPF produced from the breakdown voltage data, the CPF derived from the time to breakdown data (Figure 5-4b) shows deviation of the experimental data points both from the distribution reference as well as outside the confidence banding. However, given that the dataset still conforms to a normal distribution, as a result of the p-value of the data being above 0.05, it is still possible to obtain the predicted values of time to breakdown at all percentiles of interest; 3268ns ($t_{10\%}$), 4192ns ($t_{50\%}$) and 5378ns ($t_{95\%}$).

5.2.1.2. Breakdown of synthetic ester in the ‘As Received’ condition

When under microsecond impulse stress the measured breakdown voltage and associated time to breakdown for each of the ten breakdowns of a given sample of the synthetic ester in the ‘As Received’ condition show no clear upward or downward trend for any of the three liquid samples tested under either energisation polarity. Based on the absence of any visible upward or downward trend in breakdown voltage, or time to breakdown, it is reasonable to pool these datasets for the purpose of mean value analysis (sample size n = 10).

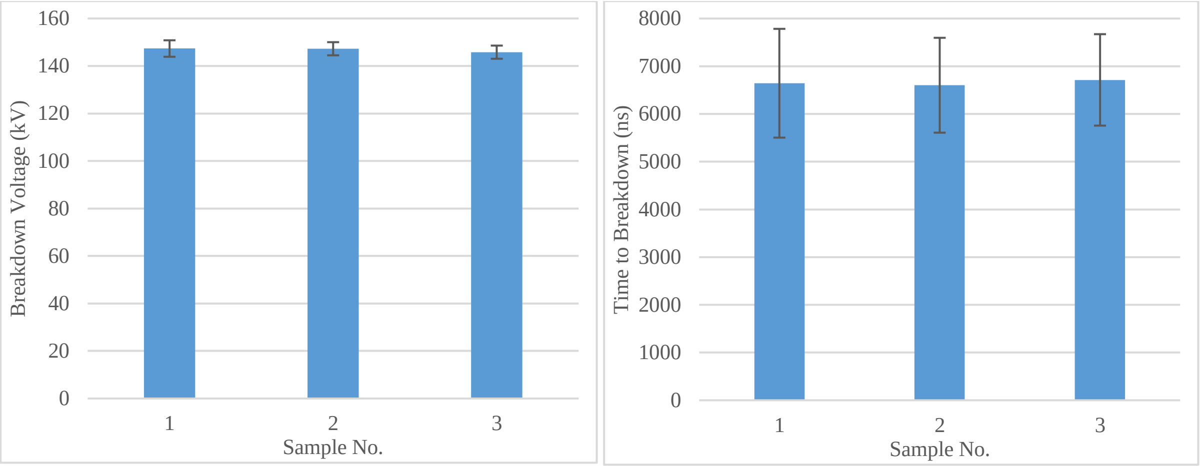


(a) (b)

Figure 5-5; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Once again a statistically significant difference may not be present in the average breakdown voltages of the three tested samples; due to the overlapping of the 95% confidence error bars. From Figure 5-5a it is clear that breakdown of the synthetic ester samples under positive microsecond impulse consistently occurred over a small range of voltages with only a 5% difference between the highest and lowest average values.

When examining the data on the average time to breakdown of the synthetic ester samples identical behaviour to that of breakdown voltage is observed. Namely that the shortest average time to breakdown corresponds to the sample with the lowest breakdown voltage (Sample 2; 883ns). While the highest average breakdown voltage and longest time to breakdown are associated with Sample 3 (987ns). As with the average breakdown voltage data, statistically significant difference in the average time to breakdown between liquid samples may not be present at the selected degree of confidence. This lack of statistical difference allows for the grouping of the three sample datasets to allow for cumulative probability analysis (n = 30).

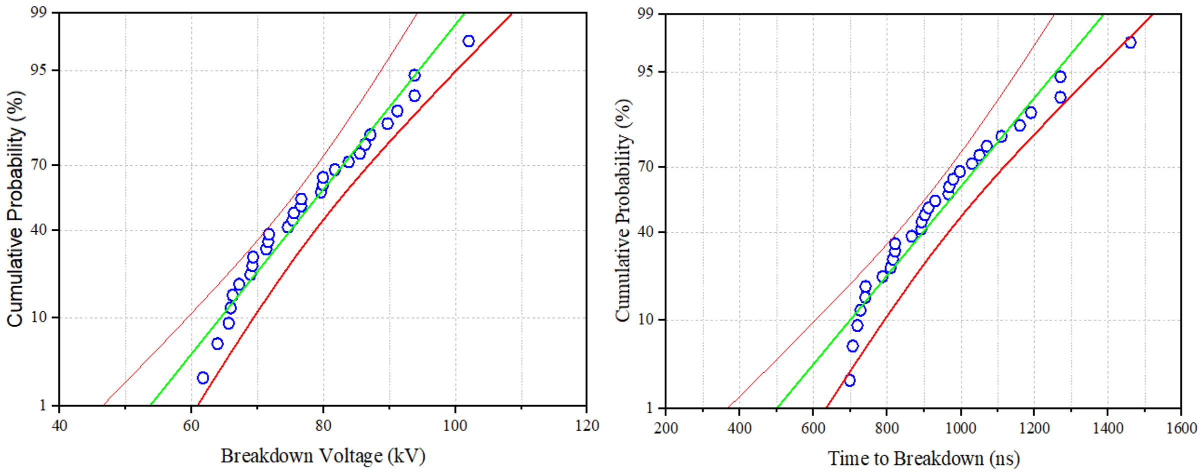


(a) (b)

Figure 5-6; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When the synthetic ester samples were stressed with negative microsecond impulse again statically significant difference in the calculated average breakdown voltages of each liquid sample may not be present at the selected degree of confidence. There is almost no variance in calculated average values of breakdown voltage for each synthetic ester samples; with a <1% difference seen in the highest (Sample 1; 147kV) and lowest (Sample 3; 146kV) values of average breakdown voltage. This is due to the breakdown of the fluid under this negative impulse occurring close to the peak nominal output of the impulse circuit (150kV). Again, the probable lack of statistical difference between samples allows for the grouping of the sample data for the purpose of CPF analysis.

When evaluating the average values of time to breakdown for the synthetic ester samples under negative microsecond impulse (Figure 5-6b) it is apparent that breakdown took place close to the peak of the impulse. This can be seen in the values of time to breakdown for all three samples possessing times almost that of the nominal rise-time of the impulse (7000ns); Sample 1; 6644ns, Sample 2; 6602 and Sample 3; 6714ns. Like the average values of negative breakdown voltage, it is probable that no statistical variation in the calculated values of time to breakdown between samples exists, with all 95% confidence error bars seen to overlap. Unlike the breakdown voltage data, the highest average for the time to breakdown parameter was calculated for Sample 3, which exhibits the lowest breakdown voltage. Given the closeness of the samples breakdown voltages (<1%) this discrepancy is attributed to the spread of the time to breakdown data which is much larger than that of the breakdown voltage data. This is a consequence of all breakdowns occurring at the peak of the voltage impulse were the change in voltage is much lower than the change in time.



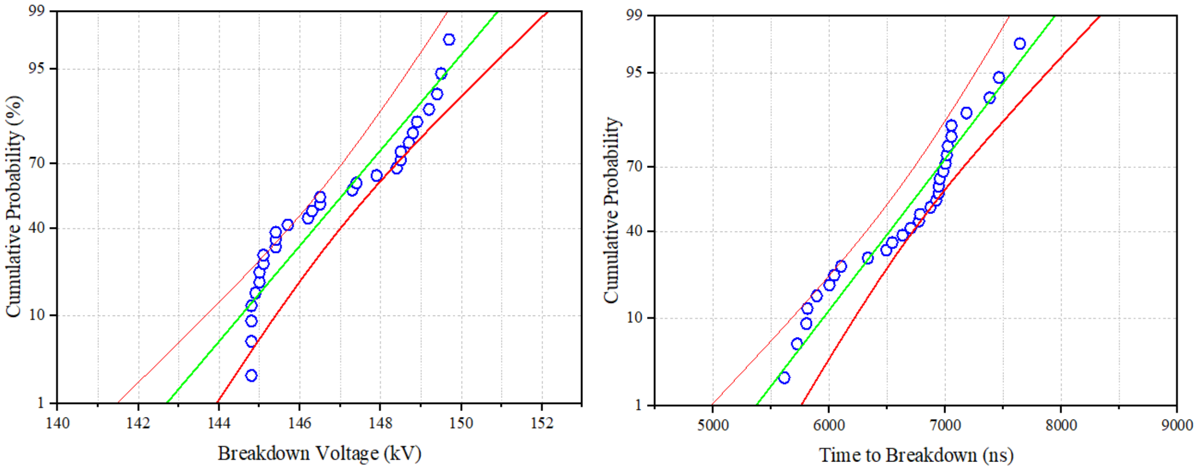
(a)

(b)

Figure 5-7; *Probability plots for 'As Received' synthetic ester; CPFs for positive 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The cumulative probability functions generated from the experimental data gathered during the testing of the synthetic ester under positive polarity microsecond impulse can be seen in both Figure 5-7a and 5-7b. The normal distribution of the breakdown voltage data was confirmed by the KS normality test (p-value 0.85). When the CPF associated with the breakdown voltage of the fluid (Figure 5-7a) is examined it can been seen experimental data is in excellent agreement with the predicted normal distribution with all data points close to the reference line. The predicted levels of breakdown voltage for the 10th 50th and 95th percentiles are shown to be 64kV, 78kV and 94kV respectively.

The experimental data gathered on the time to breakdown of the synthetic ester under positive microsecond impulse also follows a normal distribution (p-value 0.95). Given the data possesses such a high p-value it is unsurprising that the experimental data is in good agreement with the distribution reference, though some deviation is present at the upper and lower extremities of the CPF. From the CPF, given in Figure 5-7b, it is possible to extract the time to breakdown associated with 10%, 50% and 95% probability of breakdown; 699ns, 943ns and 1257ns respectively.



(a)

(b)

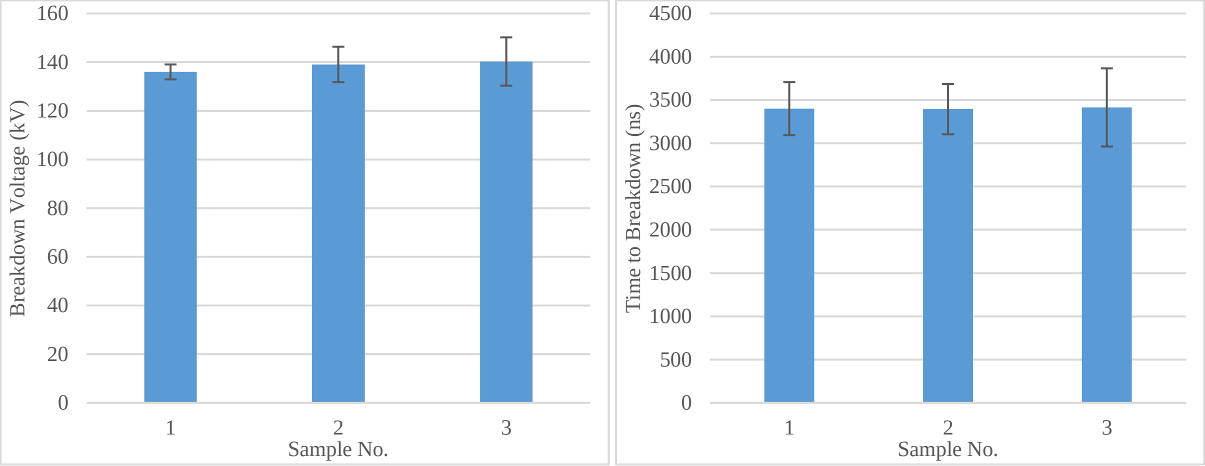
Figure 5-8; *Probability plots for 'As Received' synthetic ester; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from breakdown voltage data obtained when the synthetic ester samples were stressed with negative microsecond impulse can be seen in Figure 5-8a. While there is clear deviation of the experimental breakdown voltage data from the predicted distribution line the data was still shown to be distributed normally with a KS p-value of 0.23. From the above Figure (5-8a), the predicted breakdown voltages corresponding to 10%, 50% and 95% probability of breakdown were taken to be 145kV, 147kV and 150kV respectively.

Figure 5-8b shows the CPF generated from the time to breakdown data obtained when the synthetic ester was stressed with negative microsecond impulse, which was confirmed to be normally distributed by the KS normality test (p-value 0.45). While there is some deviations from the predicted normal distribution line all data is contained within the upper and lower confidence banding. From Figure 5-8b the values of time to breakdown corresponding to a 10%, 50% and 95% probability of breakdown were shown to be 5945ns, 6653ns and 7563ns respectively.

5.2.1.3. Breakdown of natural ester in the 'As Received' condition

The breakdown voltage and time to breakdown for the ten shots applied to each of the natural ester samples when in the 'As Received' condition and stressed with microsecond impulses of both positive and negative polarity contained no discernible upward or downward trend as shot number is increased. Both increases and decreases in both breakdown parameters were observed across the datasets of each individual liquid sample for both positive and negative energisation. Thus, the decision was taken to group each set of ten shots into three discrete datasets, one for per liquid sample, to allow for mean value analysis of both breakdown voltage and time to breakdown.

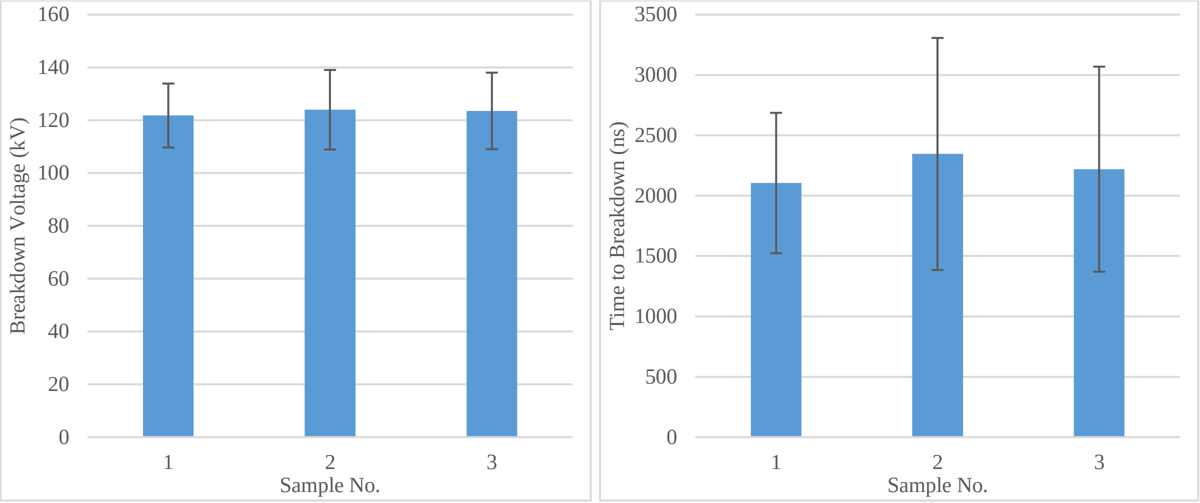


(a) (b)

Figure 5-9; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

As can be seen in Figure 5-9a statistically significant difference may not exist in the level of voltage required to cause breakdown of any of the natural ester samples when the fluid is under positive microsecond impulse stress. The difference in average levels of breakdown voltage for each of the three samples is ~3% with breakdown seen to occur between the range of 136-140kV. Although as aforementioned, as the confidence intervals overlap this difference may not represent statistical significance.

Time to breakdown data (Figure 5-9b) shows identical behaviour to that of breakdown voltage with each of the three samples requiring what can be assume to be, given the overlap in the confidence intervals, a similar time for breakdown to occur. Unsurprisingly the longest time to breakdown is seen for the data in Sample 3 (3414ns), though unlike the data in Figure 5-9a, the shortest time to breakdown relates to that of Sample 2 (3394ns). Given that the lowest value of average breakdown voltage was calculated for Sample 1, rather than Sample 2, it would be expected that the shortest average time to breakdown would also be associated with Sample 1. This is clearly not the case, though Sample 2 and Sample 1 do possess very similar average values of time to breakdown; 3394ns and 3400ns respectively. It is assumed that the discrepancy in breakdown voltage and time to breakdown results are as a consequence of slight distortions in the experimental waveform likely originating from parasitic elements (inductance and capacitance) in the experimental system rather than a difference in the spread of the data given the comparable size of the confidence intervals associated with the sample data.

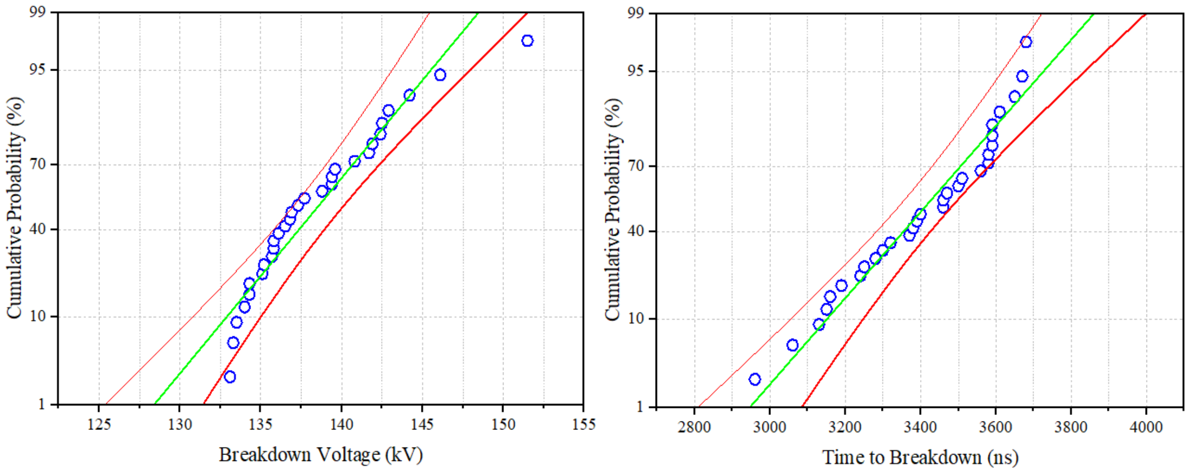


(a) (b)

Figure 5-10; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

When the calculated average breakdown voltages of the three ‘As Received’ natural ester samples under negative microsecond impulse are evaluated it can be said that, due to the overlap in the 95% confidence intervals, breakdown likely occurs at a similar level of voltage for all samples. Figure 5-10a does show a small ~2% variation between individual samples, with the highest average value occurring for Sample 2 (124kV) and the lowest for Sample 1 (122kV).

Average time to breakdown data relating to the breakdown of the ‘As Received’ natural ester samples when under negative microsecond impulse stress (Figure 5-10b) is in good agreement with that of the breakdown voltage (Figure 5-10a), with the longest average time calculated for Sample 2 (2346ns) and the shortest for Sample 1 (2105ns). While this trend is identical to that of the breakdown voltage, the difference between the highest and lowest values of average time to breakdown is greater than that of breakdown voltage (10% as compared with 2%). This is attributed to the wider spread of the time to breakdown data as compared with breakdown voltage, which is demonstrated by the larger error bars that exist for the time to breakdown data. Again, the potential statistical similarity in the average time to breakdown of each sample allows for the pooling of the datasets into a single group for the means of CPF analysis.

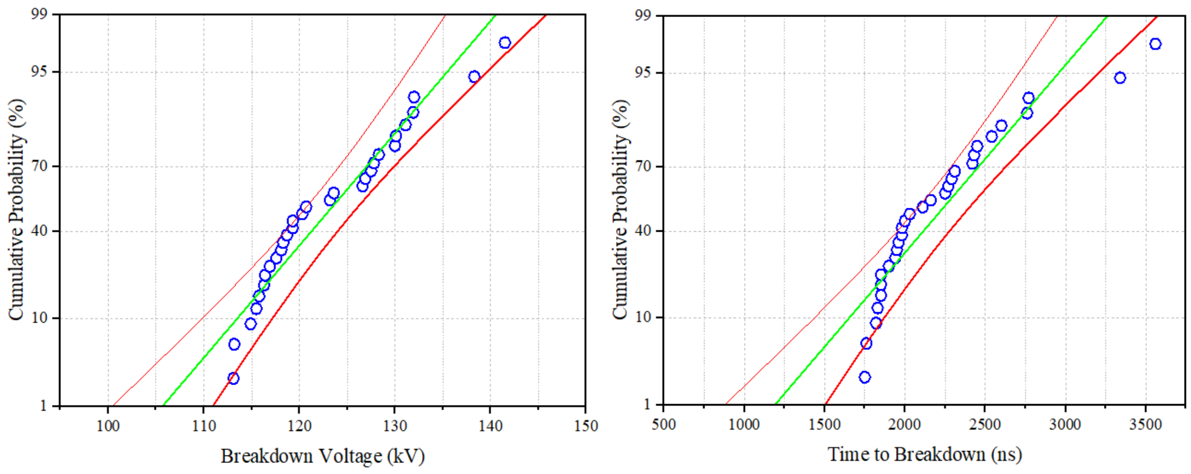


(a) (b)

Figure 5-11; *Probability plots for 'As Received' natural ester; CPFs for positive 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The distribution of the experimental data gathered on the positive polarity breakdown voltage of the ‘As Received’ natural ester samples was confirmed to be normal through the KS normality test, with the data shown to have a goodness of fit coefficient (p-value) of 0.59. The CPF produced from the data can be seen in Figure 5-11a, it is clear that the experimental data is in good agreement with the predicted distribution; with all but two data points residing within the upper and lower confidence bands. From the CPF the predicted values of voltage which will result in breakdown of the fluid at the percentiles of interest have been extracted; these correspond to 133kV (10th), 138kV (50th) and 146kV (95th).

The experimental data relating to the time to breakdown of the ‘As Received’ natural ester when under positive microsecond impulse voltage was also shown by the KS normality test to be distributed normally (p-value 0.76). Given this high coefficient, it is unsurprising that the data sits close to the predicted distribution reference line with all data contained within the confidence bands. Predicted values of time to breakdown associated with 10%, 50% and 95% probability of breakdown are 3151ns, 3403ns and 3726ns respectively.



(a) (b)

Figure 5-12; *Probability plots for 'As Received' natural ester; CPFs for negative 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained from the stressing of ‘As Received’ natural ester with negative microsecond impulses was confirmed to be normally distributed with a p-value for the dataset of 0.38. All experimental data points in the CPF, shown in Figure 5-12a, can be seen to reside within the confidence banding, with most siting on or close to the distribution reference line. The predicted levels of breakdown voltage necessary to result in a 10%, 50% and 95% likelihood of liquid breakdown were shown by the CPF to be 114kV, 123kV and 135kV respectively.

The CPF associated with the time to breakdown of the ‘As Received’ natural ester when exposed to negative microsecond impulse can be seen in Figure 5-12b. The data was shown to follow a normal distribution, with a p-value of 0.33; very similar to that given for the breakdown voltage of the fluid (0.38). Unlike the breakdown voltage data, which is equally spread across the CPF, a number of data points show breakdown requiring the same time to breakdown (1850ns). Despite this it is possible to extract the predicted values of time to breakdown at the percentiles of interest; with 1654ns, 2224ns and 2955ns corresponding to a 10%, 50% and 95% probability of breakdown respectively.

5.2.1.4. Summary of breakdown of dielectric fluids in ‘As Received’ condition

The preceding sections have provided the experimental data relating to the breakdown of the three chosen dielectric fluids when in the ‘As Received’ condition under microsecond impulse voltage of both positive and negative polarity. The average breakdown voltage and associated time to breakdown of each of the fluids, as well as the cumulative probability function of the data under both energisation polarities was analysed with this data summarised in Table 5-1 below.

Table 5-1; *Average breakdown voltage and time to breakdown of 'As Received' dielectric fluids when stressed with 7µs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	123 ± 5.7kV	119kV	129kV	~1
	MIDEL 7131	78 ± 17.5kV	64kV	94kV	0.85
	Envirotemp FR3	138 ± 7.3kV	133kV	146kV	0.59
Negative impulse	Shell Diala S4	142 ± 4.6kV	139kV	147kV	~1
	MIDEL 7131	147 ± 3kV	145kV	150kV	0.23
	Envirotemp FR3	123 ± 12.7kV	114kV	135kV	0.76
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	2247 ± 295ns	2025ns	2533ns	0.69
	MIDEL 7131	943 ± 324ns	699ns	1257ns	0.95
	Envirotemp FR3	3403 ± 334ns	3151ns	3726ns	0.38
Negative impulse	Shell Diala S4	4192 ± 1226ns	3268ns	5378ns	0.27
	MIDEL 7131	6653 ± 940ns	5945ns	7563ns	0.43
	Envirotemp FR3	2224 ± 756ns	1654ns	2955ns	0.33

The average breakdown voltage and time to breakdown of the chosen dielectric fluids in the 'As Received' condition under both positive and negative microsecond impulse are provided above in Table 5-1. V_{mean} and t_{mean}, relate to the average values of a given parameter ± the 95% confidence intervals as calculated from the entire dataset (n = 30) for a given liquid and impulse polarity. $V_{10\%}$ to $V_{95\%}$ represent the probability values of the breakdown parameters for a given liquid as predicted by the CPF with the KS goodness of fit coefficients (p-values) of the data also provided. When under positive microsecond impulse stress all three liquids require a statistically different level of voltage to facilitate breakdown. It has been shown from the experimental work conducted that the natural ester exhibits the highest breakdown strength of the three fluids when under positive microsecond impulse, 12% higher than the mineral oil and 77% greater than that of the synthetic ester. This is also reflected in the time to breakdown of each of the fluids under positive voltage stress, where again the natural ester has the best performance and the synthetic ester the worst. Breakdown of the natural ester fluid takes on average 1.5 and 3.6 times longer than that of the mineral oil and synthetic ester respectively. However, when the impulse is of negative polarity the inverse is true with the synthetic ester now offering the best dielectric performance and the natural ester the worst. Under such negative microsecond impulse, the experimental data shows that the average breakdown voltage of the synthetic ester is now the highest and is shown to likely be statistically similar to that of the mineral oil with only a 4% difference in average values. Breakdown of the natural ester under these negative impulse conditions occurs at a statistically lower level of voltage than both the synthetic ester and mineral oil, with average values as much as 20% below that of the synthetic ester. Again, this behaviour is mirrored in the average values of time to breakdown calculated for the three fluids with the synthetic ester requiring the longest time to breakdown and the natural ester the shortest. However, unlike the breakdown voltage data there now exists a statistically significant difference between all three liquids. This is as a result of breakdown of the synthetic ester taking place near the peak, or plateau, of the voltage impulse where the change in voltage is much smaller than the change in time to breakdown.

When examining the breakdown voltages predicted by the CPF when the microsecond impulse is of positive polarity breakdown of the natural ester is projected to occur at a higher level of voltage than both the mineral oil and synthetic ester at all percentiles of interest; ~12% greater than the mineral and between 50% to 100% higher than that of the synthetic ester. Under this positive voltage stress, the breakdown of the synthetic ester is predicted to occur over the widest range of values; attributed to the experimental breakdown of both the mineral oil and natural ester taking place close to the nominal peak amplitude of the energising impulse. When the impulse is of negative polarity the predictions made by the CPF analysis contrast with those under positive voltage. Now the breakdown of the synthetic ester is shown to be higher at all percentiles of interest with breakdown predicted to be a much as 4% and 27% higher than that of the mineral oil and natural ester respectively. The range of predicted values of breakdown voltage is now the narrowest for the synthetic ester and the widest for the natural ester, which again is the inverse to the predictions made by the CPF when the impulse is of positive polarity.

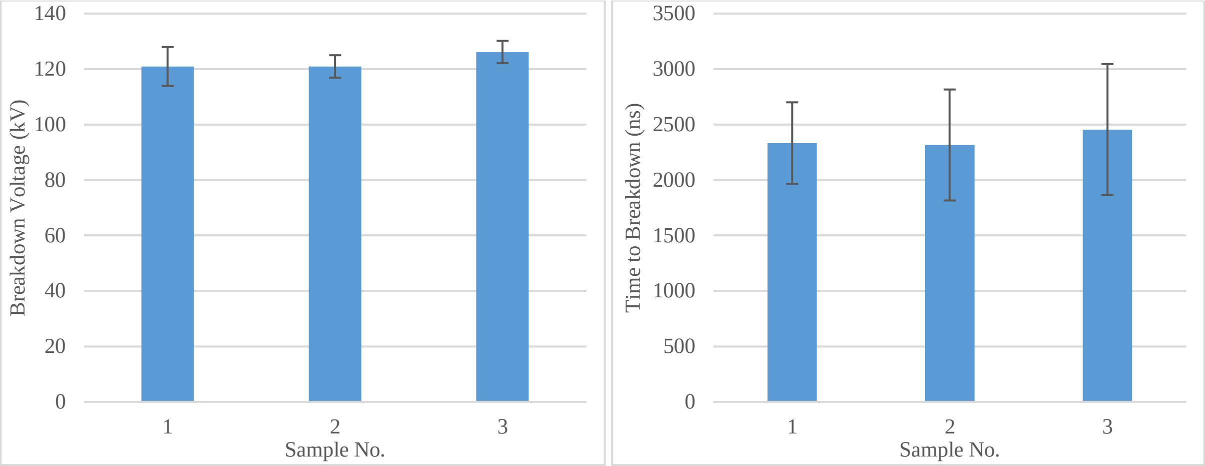
The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow the same trend seen in the predicted breakdown voltage data, with the natural ester shown to require the longest time to breakdown of all three dielectric liquids at all percentiles of interests and the synthetic ester the shortest. Again, the greatest spread of predicted values is seen in the data associated with the breakdown of the synthetic ester, while the breakdown of the natural ester occurs over the narrowest. As aforementioned, this is as a result of the point on the voltage impulse at which breakdown of the fluids occurs. When the impulse is of negative polarity the longest values of time to breakdown are predicted, as with negative breakdown voltage, for the synthetic ester while those for the natural ester are the shortest. Interestingly the range of times at which the breakdown of the synthetic ester will occur do not span the widest range, this is reserved for those of the mineral oil. This was not the case when the impulse was positive where the fluid that exhibits the longest time to breakdown also possesses the widest range of predicted values. This contrasting behaviour under negative energisation has been attributed to the breakdown of the synthetic ester occurring at a more consistent level of voltage and thus time to breakdown than that of the mineral oil.

5.2.2. Breakdown of liquids in the 'Ambient humidity' condition

The proceeding sections present and discuss the results gathered on the bulk breakdown performance of the chosen dielectric fluids in the 'Ambient humidity' condition. Fluids in this state possess relative humidity of ~35%. As described in Section 3.3.1, the desired level of relative humidity was achieved by allowing the fluids, which were in open containers, to sit within the laboratory environment until the relative humidity of the fluid reached equilibrium with ambient levels.

5.2.2.1. Breakdown of mineral oil in the 'Ambient humidity' condition

The values of breakdown voltage and time to breakdown measured for the ten breakdowns of each of the three mineral oil samples shows no clear trend, either upward or downward, across the ten breakdowns of each sample. This absence of discernible upward or downward tendency within the data has allowed for the grouping of the data collected for each sample into three discrete datasets each consisting of ten breakdowns which will be used for the process of mean value analysis.



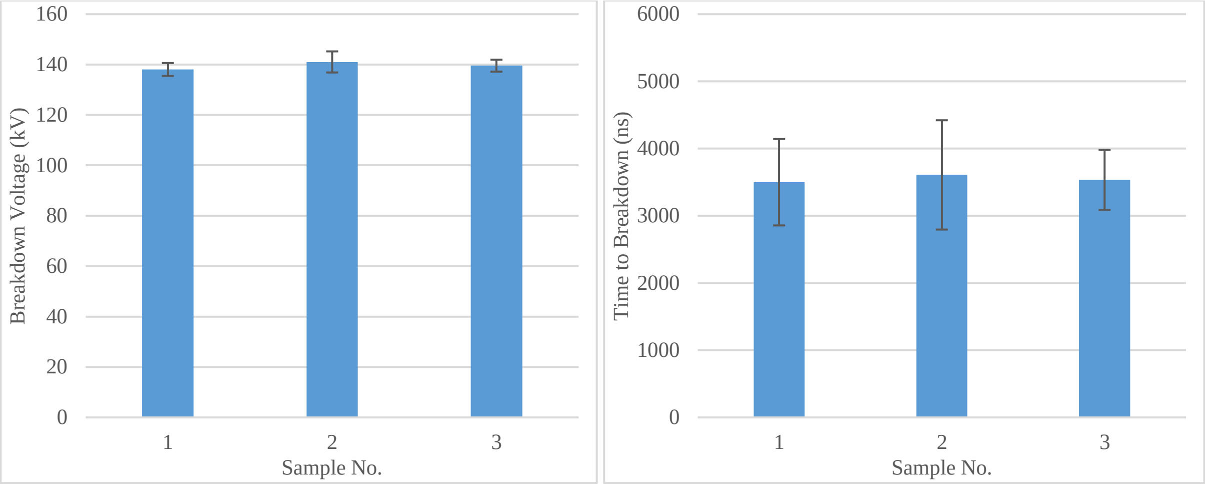
(a)

(b)

Figure 5-13; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average values of breakdown voltage for each of the ‘Ambient humidity’ mineral oil samples when under positive microsecond impulse stress, given in Figure 5-13a, show that statistical difference between samples may not exists at the selected degree of confidence. Despite the difference in sample-to-sample breakdown voltage, it is still possible to group the three datasets into one single group given the probable lack of statistical difference between sample means.

From the data presented in Figure 5-13b it can be said that due to the overlapping of the 95% confidence intervals, as with breakdown voltage, all three samples are likely to require a similar time to breakdown. A slightly larger difference is present in the average values than that of the breakdown voltage (6% as compared with 4%), with this attributed to the wider spread of the time to breakdown data; confirmed with the larger error bars associated with this data. Again, the likely absence of statistical difference between samples allows the three experimental datasets to be pooled for the purpose of CPF analysis.

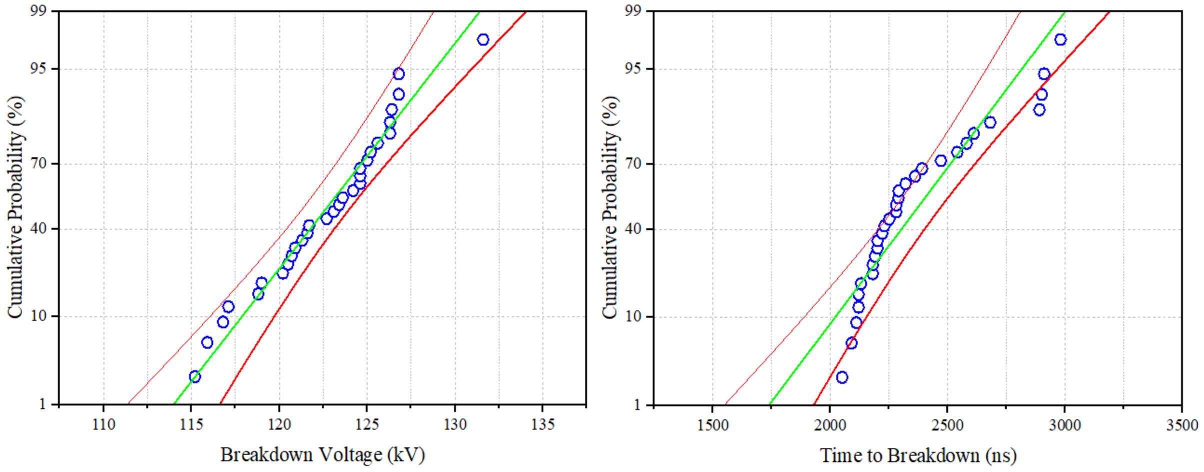


(a) (b)

Figure 5-14; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Figure 5-14a shows the average breakdown voltage obtained for the mineral oil samples in the ‘Ambient humidity’ condition when stressed with negative microsecond impulse. From the figure, it is evident that the 95% confidence intervals overlap for all samples and thus it can be assume that it is likely that breakdown occurs at a similar level of voltage. Breakdown of the samples is also seen to occur over a very small range of voltage values (138kV to 141kV), demonstrated with the small size of the confidence intervals.

The average time to breakdown data obtained when the ‘Ambient humidity’ mineral oil samples were stressed with negative microsecond impulse (Figure 5-14b) shows similar behaviour to that of the breakdown voltage data, but with a slightly greater difference between average values (4% as compared with 2% for the voltage data). The observed differences in the time to breakdown of the individual liquid samples again, as with breakdown voltage, can be assumed not to be of statistical significance as the 95% confidence intervals overlap.

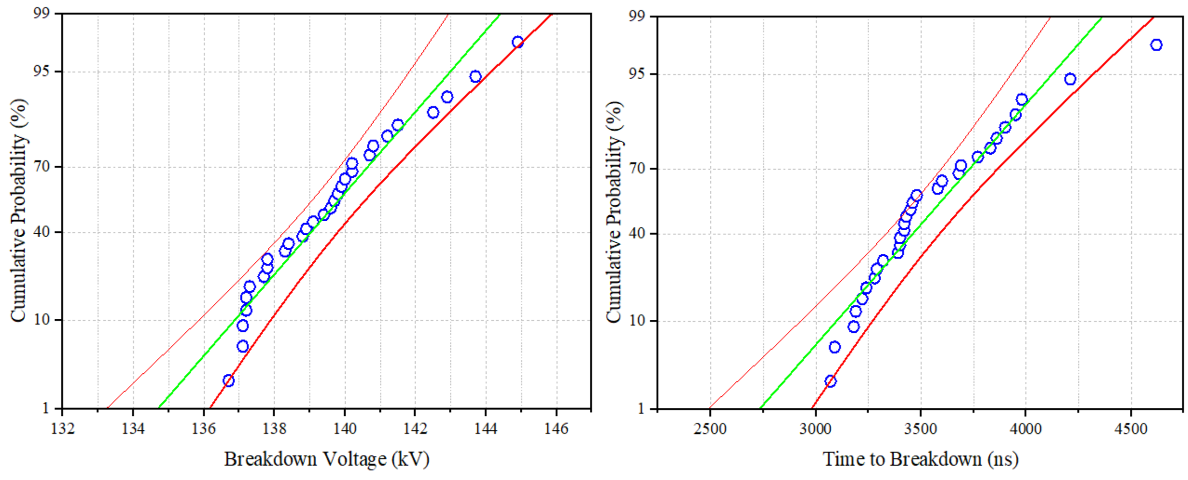


(a) (b)

Figure 5-15; *Probability plots for 'Ambient humidity' mineral oil; CPFs for positive 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from the experimental data obtained from the testing of the ‘Ambient humidity’ mineral oil under positive microsecond impulse has been given in Figure 5-15a. The distribution of the experimental data was shown to be normal through the KS normality test, delivering a p-value of 0.99. Given this goodness of fit coefficient, it is unsurprising that the majority of the experimental data points sit on the distribution reference line. From the CPF shown in Figure 5-15a the voltages at which 10%, 50% and 95% probability of breakdown will occur have been taken, with these being 118kV, 123kV and 129kV respectively.

The associated time to breakdown data was also subjected to the KS normality test with this too shown to follow a normal distribution (p-value 0.11). This low p-value has resulted in the time to breakdown data taking a much differing profile to that of the breakdown voltage, with 17% of the experimental data points placed outside of the confidence banding and ~50% deviating from the distribution reference line. Nevertheless, it is still possible to extract the values of time to breakdown at which a 10%, 50% and 95% likelihood of breakdown will occur; 2020ns, 2368ns and 2814ns respectively.



(a) (b)

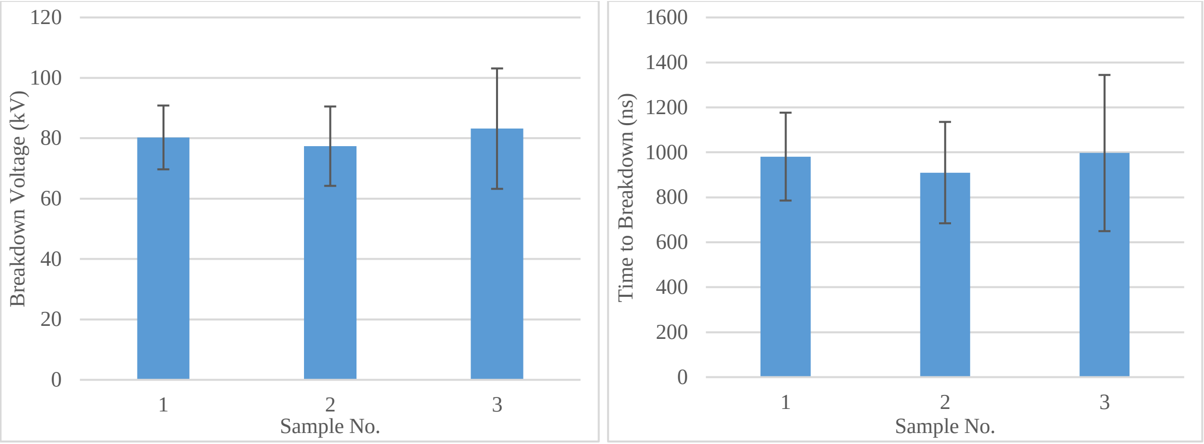
Figure 5-16; *Probability plots for 'Ambient humidity' mineral oil; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The experimental data pertaining to the stressing of the ‘Ambient humidity’ mineral oil with negative microsecond impulse follows a normal distribution; confirmed with a KS normality test p-value of 0.9. As can be seen from the CPF, given in Figure 5-16a, the data is in excellent agreement with the predicted distribution reference line. That said, it is clear from Figure 5-16a that 17% of breakdowns occurred at the same level of voltage (137kV). It is however still possible to take the predicted values of breakdown voltage at all percentiles of interest. From the CPF these voltages are predicted to be 137kV (10th), 140kV (50th) and 143kV (95th).

The time to breakdown associated with the stressing of the mineral oil in ‘Ambient humidity’ condition with negative microsecond impulse is shown in Figure 5-16b. This data is also distributed normally, though does not fit as well with the distribution as that of the breakdown voltage (p-value of 0.28 compared with 0.9 for breakdown voltage data). Despite this relatively low p-value, all but one experimental data point is contained within the confidence banding, with a large majority residing on or close to the distribution reference line. It is therefore possible to take the predicted values of time to breakdown for all percentiles of interest. From the CPF it is predicted that voltage application for 3098ns, 3547ns and 4123ns will result in a 10%, 50% and 95% probability of breakdown respectively.

5.2.2.2. Breakdown of synthetic ester in the 'Ambient humidity' condition

This section will present and discuss the results gathered from the testing of the synthetic ester MIDEL 7131 when in the 'Ambient humidity' condition. Liquid samples were stressed with microsecond impulses of both positive and negative polarity in accordance with the testing methodology described in Section 3.6.1. When the ten individual breakdowns of each liquid sample were examined no clear tendency in breakdown voltage or time to breakdown was identified, irrespective of the impulse polarity, meaning it is reasonable that the ten shots are grouped into a single dataset, one for each liquid sample, to allow for mean value analysis to be undertaken.

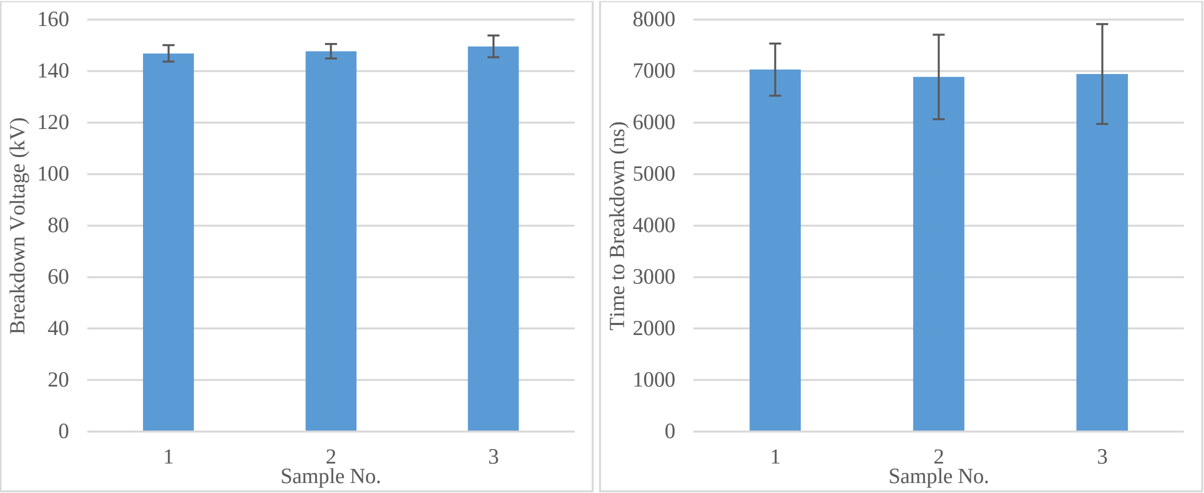


(a) (b)

Figure 5-17; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the synthetic ester samples in the 'Ambient humidity' condition when stressed with positive microsecond impulse can be seen in Figure 5-17a. From the data presented, it can be assumed that the breakdown of each of the liquid samples is likely to occur at a similar level of voltage. Given this likelihood of the presence of statistical similarity in sample-to-sample breakdown voltage it is possible to group the ten shot averages into one single dataset (n = 30) for the purpose of cumulative probability analysis.

The average time to breakdown of each of the three 'Ambient humidity' samples of the synthetic ester obtained when stressing the fluid with microsecond impulse are provided in Figure 5-17b. Identical behaviour is observed in the time to breakdown of each sample as that of the breakdown voltage, with the longest average time to breakdown calculated for Sample 3 (997ns) while the shortest corresponds to Sample 2 (910ns). This small (9%) difference in calculated average values of time to breakdown however may not be statistically significant given the overlapping of the 95% confidence intervals between samples. Moreover, this likely lack of statistical difference between any of the sample averages; means that the pooling of sample data is possible to allow for CPF analysis.

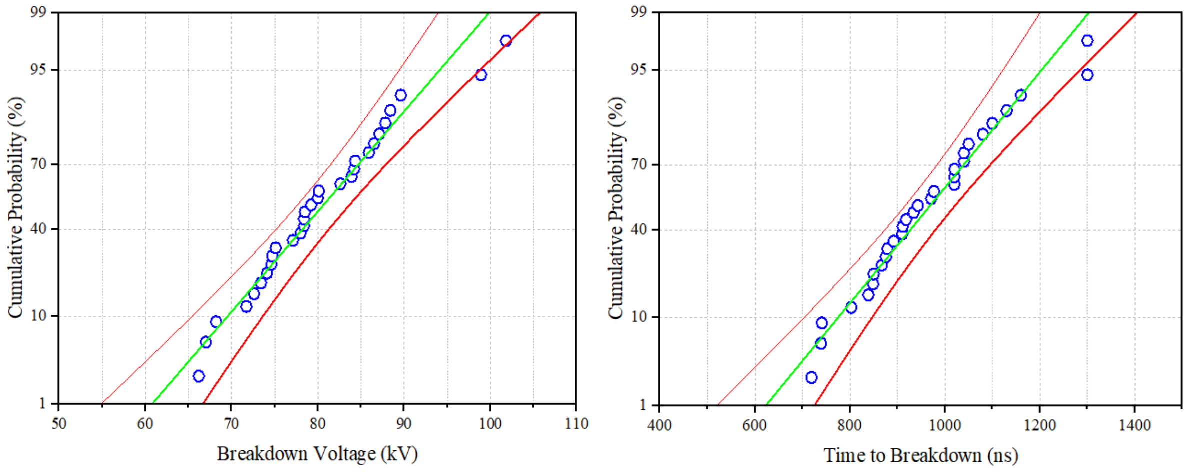


(a) (b)

Figure 5-18; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The calculated average breakdown voltages for the three 'Ambient humidity' synthetic ester samples when under negative microsecond impulse stress have been given above (Figure 5-18a). It is evident that all confidence intervals overlap and therefore statistical difference may not exist in the breakdown voltage of the samples at the selected degree of confidence. As breakdown takes place near the peak of the voltage impulse the difference between average values is only 1%. This probable lack of statistical difference between sample means will allow for the grouping of the data into a single dataset (n = 30).

Figure 5-18b provides the average time to breakdown calculated for each 'Ambient humidity' sample of the synthetic ester. As with the data in Figure 5-18a, the time to breakdown of each sample is shown to likely be statistically similar. However, unlike breakdown voltage the longest time to breakdown was calculated for Sample 1 (7028ns), not Sample 3 (6943ns), with the shortest time to breakdown associated with Sample 2 (6888ns). Given that the average values are so close to the nominal peak rise-time of the impulse (7000ns) this can be attributed to the breakdown of the synthetic ester samples taking place near the peak or on the plateau of the negative voltage impulse when the change in voltage is minimal as compare with the change in time.

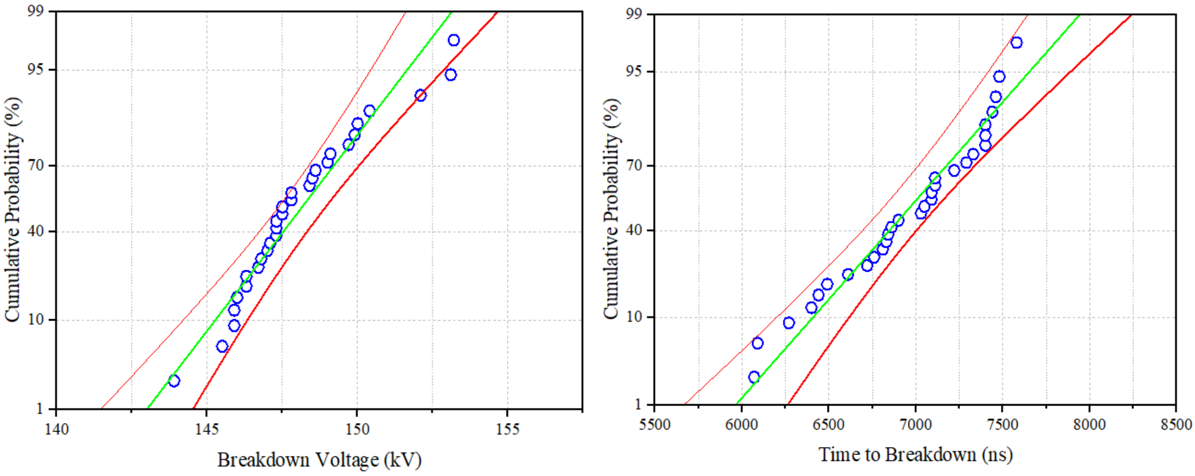


(a) (b)

Figure 5-19; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for positive 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

Figure 5-19a shows the CPF produced from the data gathered when ‘Ambient humidity’ samples of the synthetic ester were stressed with positive microsecond impulse. The experimental data was confirmed to be distributed normally with application of the KS normality test (p-value 0.92). Given this p-value represents a close to perfect fit with the distribution it is of no surprise that all but three data points sit exactly on the distribution reference line. From the CPF the voltages associated with 10%, 50% and 95% probability of breakdown have been extracted; 70kV, 80kV and 94kV respectively.

The cumulative probability function generated from the time to breakdown data (Figure 5-19b) shows excellent conformance to the normal distribution reference; with this supported by a KS p-value of ~1. As is the case for the breakdown voltage data, such a high p-value ensures that the experimental data is very close to a perfect fit to the expected distribution with the only deviation from the predicted reference occurring at the extremities of the percentile range and all but one data point contained within the confidence bands. From the CPF the required time to breakdown for 10%, 50% and 95% probability of breakdown are predicted to be 775ns, 963ns and 1203ns respectively.



(a) (b)

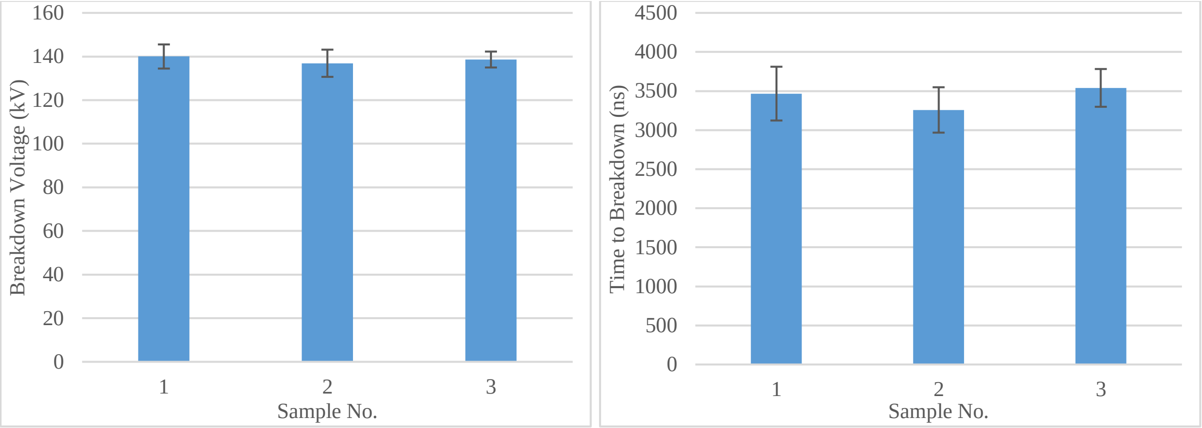
Figure 5-20; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF associated with the breakdown voltage of the ‘Ambient humidity’ synthetic ester when stressed with negative microsecond impulse has been given in Figure 5-20a. Conformance of the data to a normal distribution was assured through the use of the KS normality test, for which the data generated a p-value of 0.49. From the figure, it is clear that the experimental data fits well with the predicted distribution reference line with only a small deviation at the upper and lower percentiles and all but one data point residing within the confidence banding. From this CPF the breakdown voltages predicted to result in a 10%, 50% and 95% probability of breakdown are shown to be 145kV (10%), 148kV (50%) and 152kV (95%).

The time to breakdown associated with the testing of the synthetic ester under microsecond impulse was used to produce the CPF given in Figure 5-20b. This data was shown to be distributed normally with a p-value of 0.95. Given this high goodness of fit coefficient, it is of no surprise that the experimental data sits extremely close to the distribution reference line, with all data again contained within the confidence bands. Thus the predicted values of time to breakdown at all percentiles of interest were taken to be; 6408ns (10th), 6952ns (50th) and 7651ns (95th).

5.2.2.3. Breakdown natural ester in the 'Ambient humidity' condition

From the breakdown data obtained for the 'Ambient humidity' natural ester it was observed that when under positive and negative microsecond impulse stress there is no clear trend in the breakdown voltage or associated time to breakdown of the liquid samples. The level of breakdown voltage for each of the individual natural ester samples is seen to fluctuate up and down across the data series as is the time to breakdown for each shot; this holds true for all samples tested under both positive and negative microsecond impulse. The lack of any clear trend in the experimental data under either energisation polarity again supported the decision taken to pool sample data into suitably large dataset for the purpose of mean value analysis (n = 10).

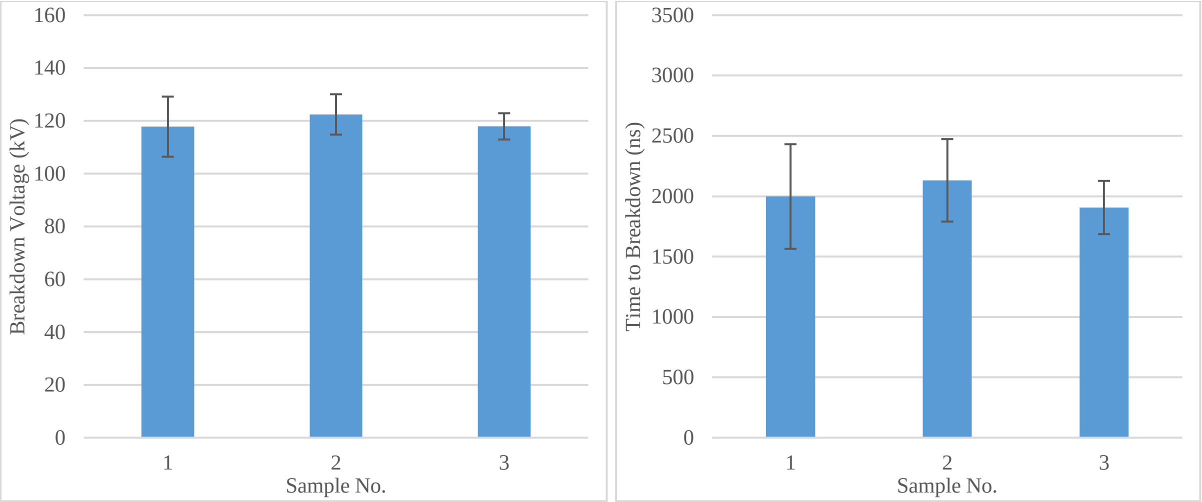


(a) (b)

Figure 5-21; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage of the 'Ambient humidity' natural ester when stressed with positive microsecond impulse is provided in Figure 5-21a. Given the overlap in the 95% confidence intervals statistically significant difference may not exists in the level of voltage required to cause breakdown of any of the natural ester samples when the fluid is under positive microsecond impulse stress. Again there is a small numerical difference in average levels of breakdown voltage between samples of only ~2% with breakdown seen to occur between the range of 137-140kV; though as aforementioned these differences may not represent statistical significance.

Time to breakdown data (Figure 5-21b) shows identical behaviour to that of breakdown voltage, with the three samples again likely to possess statistical similarity in the time required for breakdown to occur. The longest time to breakdown is seen for Sample 3 (3540ns), though unlike the data in Figure 5-21a, the shortest time to breakdown relates to that of Sample 2 (3258ns). With the highest average breakdown voltage calculated for Sample 1, it would therefore be expected that the longest average time to breakdown would also be associated with Sample 1. This is clearly not the case, though Sample 3 and Sample 1 do possess very similar average values of time to breakdown; 3467ns and 3540ns respectively. The discrepancy in breakdown voltage and time to breakdown results is assumed to be due to slight distortions in the experimental waveform originating from parasitic capacitance and inductance; as was the case with the ‘As Received’ condition natural ester (discussed in Section 5.2.1.3).



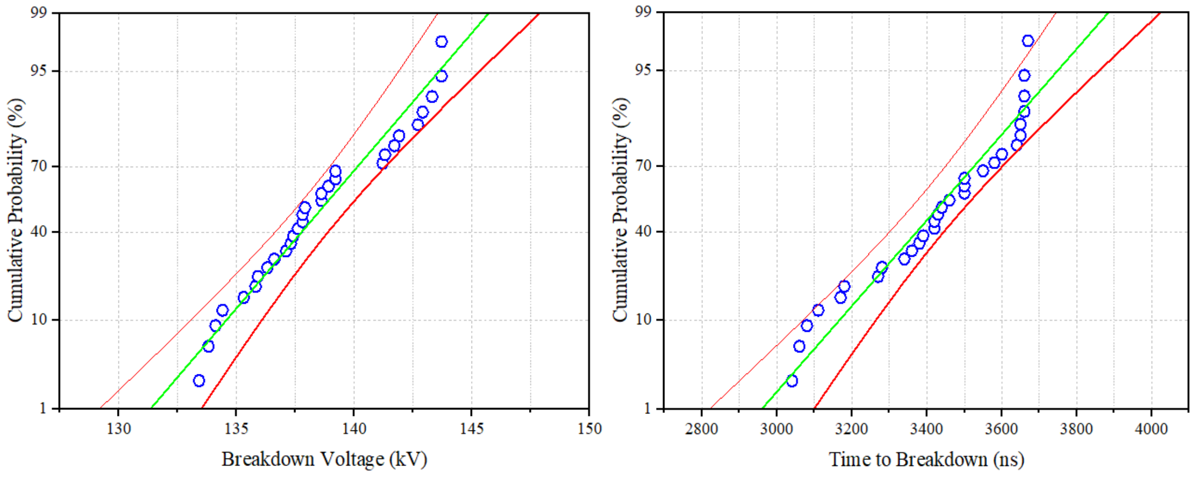
(a)

(b)

Figure 5-22; *Negative 7μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for the three natural ester samples in the ‘Ambient humidity’ condition when under negative microsecond impulse stress can be seen in Figure 5-22a. Again, due to the overlapping 95% confidence intervals, all samples can be assumed to require a similar level of voltage to result in breakdown of the fluid. Due to this probable lack of a statistically significant difference between samples, the grouping of the data into a single dataset for CPF analysis is possible.

Figure 5-22b gives the average values of time to breakdown calculated for each of the three natural ester samples. Again, there is a likely absence of statistical difference between sample averages. Time to breakdown data agrees with that of the breakdown voltage in that the longest average time to breakdown was calculated for Sample 2 (2132ns) and the shortest Sample 3 (1907ns). Interestingly, even though a <1% difference exists between the average breakdown voltages, calculated for Sample 1 and Sample 3, there is a 5% difference in the average values of time to breakdown for these two samples. This can be attributed to the spread of the data and is confirmed by the large error bar associated with Sample 1, highlighting that the data of this sample contains outliers that are affecting the mean value.

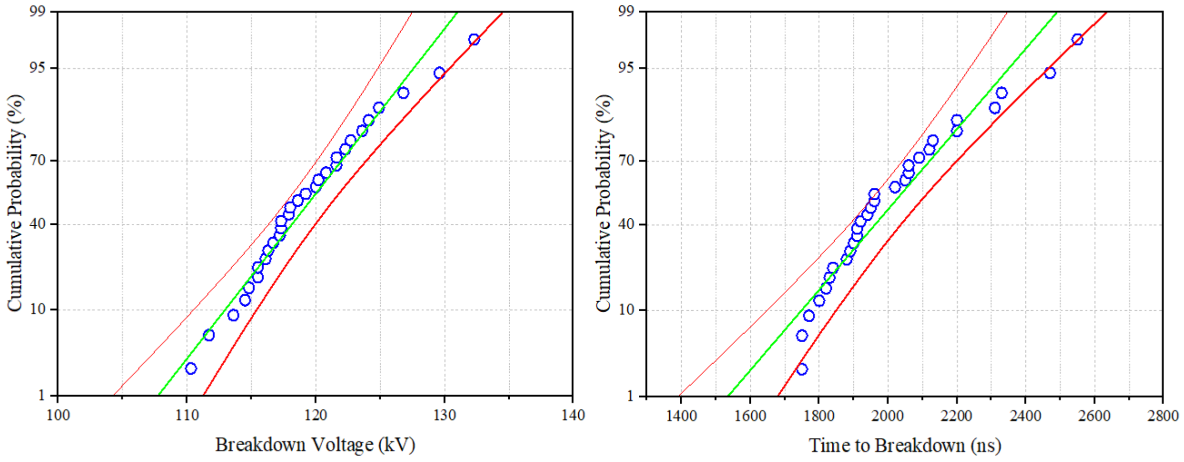


(a) (b)

Figure 5-23; *Probability plots for 'Ambient humidity' natural ester; CPFs for positive 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

Figure 5-23a gives the CPF derived from the experimental data gathered from stressing the ‘Ambient humidity’ natural ester samples with positive polarity microsecond impulse. The distribution of this experimental data was confirmed as normal by the KS normality test (p-value 0.88). As can be seen in Figure 5-23a, the experimental data is all contained within the confidence bands and is in excellent agreement with the distribution reference. From the CPF the levels of breakdown voltage predicted to result in 10%, 50% and 95% probability of breakdown have been shown to be 135kV, 139kV and 144kV respectively.

The time to breakdown data associated with the breakdown of the natural ester under positive microsecond impulse stress was also shown to follow a normal distribution through the KS normality test, with the data having a p-value of 0.96. With this p-value being so close to that of a perfect fit (1) it is unspringing that the experimental data fits well with the predicted distribution. That said, there is some deviation from the reference line at the upper and lower most percentiles, though this does not affect the ability to extract the values of time to breakdown at the percentiles of interest. From the CPF it can be seen that it will take 3166ns, 3422ns and 3749ns to result in a 10%, 50% and 95% probability of breakdown respectively.



(a)

(b)

Figure 5-24; *Probability plots for 'Ambient humidity' natural ester; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The experimental breakdown voltage data obtained during the testing of the ‘Ambient humidity’ natural ester under negative microsecond impulse follows a normal distribution (p-value 0.93). From the CPF shown in Figure 5-24a it is clear that the experimental data fits well with the predicted distribution, with all but two data points in the upper percentiles residing on the reference line. From the CPF the levels of voltage which will result in a 10%, 50% and 95% probability of breakdown have been predicted to be 113kV, 119kV and 128kV respectively.

The CPF produced from the time to breakdown data can be seen in Figure 5-24b. From the CPF it is clear the fit of this data is not as optimal as that of the breakdown voltage data; with this confirmed by the KS normality test (p-value of 0.34 for time to breakdown as compared with 0.93 for breakdown voltage). Despite this the data is still of normal distribution and thus the times to breakdown which correspond to the percentiles of interest can be taken; 1749ns (10th), 2012 (50th) and 2351ns (95th).

5.2.2.4. Summary of breakdown of dielectric liquids in the 'Ambient humidity' condition

The chosen dielectric liquids in the 'Ambient humidity' condition were stressed with microsecond impulses of both positive and negative polarity. Gathered experimental data for each of the three individual samples of the dielectric fluids was evaluated and it was shown that no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, existed; irrespective of energisation polarity. This allowed for the pooling of sample data into three discrete datasets for each of the three liquids, which was then used in mean value analysis. Evaluation of this data demonstrated that statistical difference may not exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the three discrete datasets into a larger pool for the means of cumulative probability analysis. Calculated values of the chosen breakdown parameters (breakdown voltage and time to breakdown) derived from both the mean and CPF analysis have been summarised in Table 5-2.

Table 5-2; *Average breakdown voltage and time to breakdown of 'Ambient humidity' dielectric fluids when stressed with 7µs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	123 ± 6.4kV	118kV	129kV	~1
	MIDEL 7131	80 ± 14.3kV	70kV	94kV	0.85
	Envirotemp FR3	139 ± 5.2kV	135kV	144kV	0.59
Negative impulse	Shell Diala S4	140 ± 3.5kV	137kV	143kV	~1
	MIDEL 7131	148 ± 3.7kV	145kV	152kV	0.23
	Envirotemp FR3	119 ± 9kV	113kV	128kV	0.76
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	2368 ± 461ns	2020ns	2814ns	0.69
	MIDEL 7131	963 ± 248ns	775ns	1203ns	0.95
	Envirotemp FR3	3422 ± 338ns	3167ns	3749ns	0.38
Negative impulse	Shell Diala S4	3547 ± 596ns	3098ns	4123ns	0.27
	MIDEL 7131	6952 ± 722ns	6408ns	7651ns	0.43
	Envirotemp FR3	2012 ± 350ns	1749ns	2351ns	0.33

When under positive microsecond impulse all three 'Ambient humidity' condition liquids require a statistically different level of voltage to initiate breakdown of the fluid. The natural ester was shown to have the highest dielectric strength, 13% above that of the mineral oil and 74% greater than the synthetic ester, when under positive impulse stress. This is also reflected in the time to breakdown data which shows that the natural ester requires ~45% longer to breakdown than the mineral oil and over 3.5 times that of the synthetic ester fluid. When the liquids are stressed with negative microsecond impulse inverse behaviour to that observed from the positive impulse experimentation is true. In these circumstances, the synthetic ester now exhibits the highest dielectric strength and the natural ester the lowest. Statistical difference still exists between the breakdown voltages of all three fluids with the synthetic ester requiring 6% and 24% higher voltage to result in fluid breakdown than the mineral oil and natural ester respectively. The time to breakdown obtained for the three fluids under negative microsecond impulse agrees well with that of the breakdown voltage, with again the synthetic ester requiring a statistically longer time to breakdown that both the mineral oil and the natural ester. The time to breakdown of the synthetic ester under the negative impulse conditions was shown to be approximately twice that of the mineral oil and nearly three-and-a-half times that of the natural ester fluid.

When examining the breakdown voltage under positive microsecond impulse predicted by the CPF it can be seen that the natural ester fluid requires a higher level of breakdown voltage at all percentiles of interest; between 11-14% greater than the mineral oil and 54-93% higher than the synthetic ester. The breakdown of the synthetic ester is predicted to occur over the widest range of values; attributed to the experimental breakdown of both the mineral oil and natural ester occurring at a point on the energising impulse where the change in voltage is much slower. When the impulse is negative the predicted behaviour of the fluids is inverse to that under positive voltage. Breakdown of the synthetic ester is now higher at all percentiles of interest, with breakdown predicted to be a much as 6% and 28% higher than that of the mineral oil and natural ester respectively. The range of predicted values of breakdown voltage is now the narrowest for the synthetic ester and the widest for the natural ester, which again is the inverse to the predictions made by the CPF when the impulse is of positive polarity.

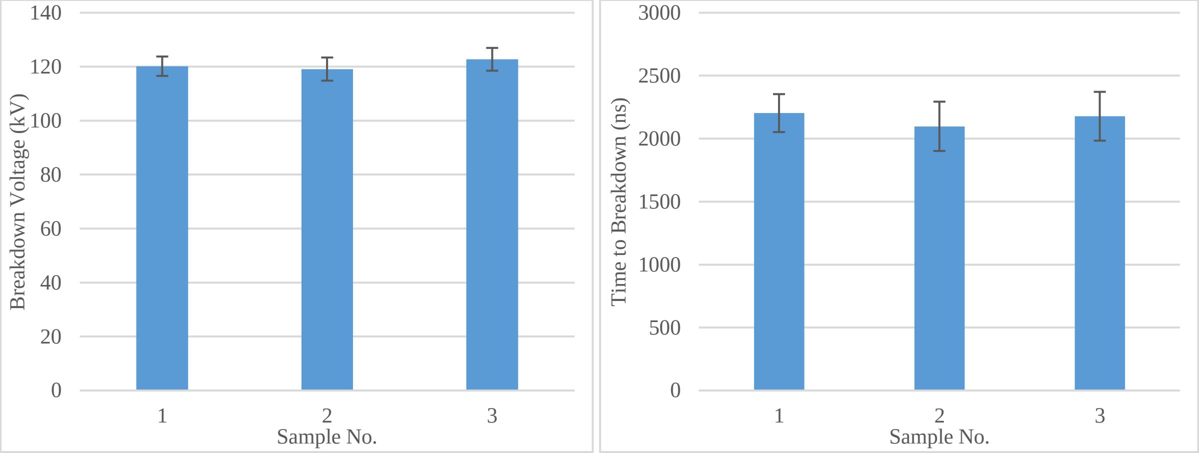
The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow the exact trend seen in the predicted breakdown voltage data, with the natural ester shown to require the longest time to breakdown of all three dielectric liquids at all percentiles of interests and the synthetic ester the shortest. However, the spread of predicted values is now largest in the data associated with the breakdown of the mineral oil, while the breakdown of the synthetic ester is now predicted to occur over the narrowest range. As aforementioned, this is as a result of the point on the experimental impulse at which breakdown of the fluids occurs. The longest values of time to breakdown when under negative voltage stress are predicted, as with breakdown voltage, for the synthetic ester while the natural ester the shortest. The range of predicted times at which the breakdown of the synthetic ester will occur now span the widest range, with those associated with the natural ester the narrowest. This is in contrast to the predictions made from the experimental data obtained under positive impulse stress where the time to breakdown of the mineral oil spanned the widest range of predicted values.

5.2.3. Breakdown of liquids in the ‘Elevated humidity’ condition

The following sections of this chapter are devoted to the discussion of experimental data obtained from testing of the chosen dielectric liquids in the ‘Elevated humidity’ condition. This state denotes liquids with the highest level of relative humidity investigated in this thesis (>70% relative humidity). To achieve such a high state of relative humidity the liquids were subjected to a humidification process; as described fully in Section 3.3.1.

5.2.3.1 Breakdown of mineral oil in the ‘Elevated humidity’ condition

Examination of the breakdown voltage and time to breakdown data obtained for the ‘Elevated humidity’ mineral oil has shown that no clear upward or downward trend exists across the ten breakdowns of each sample. This absence of discernible trends within the data has allowed for the grouping of sample data into three discrete datasets each consisting of ten breakdowns which will be used for mean value analysis.

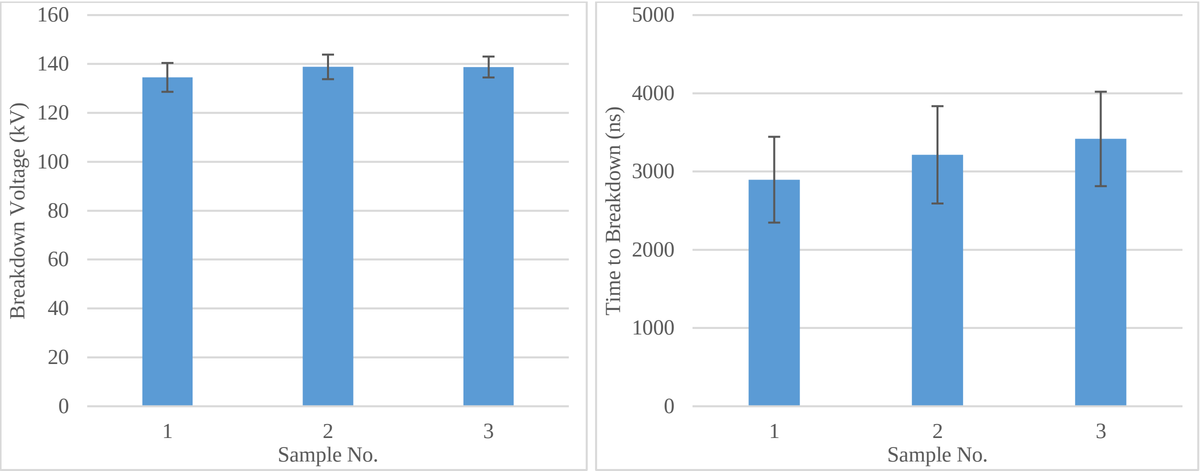


(a) (b)

Figure 5-25; *Positive 7μs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The calculated average values of breakdown voltage for each of the three ‘Elevated humidity’ mineral oil samples when under microsecond impulse stress have been given in Figure 5-25a. Breakdown of the three samples can be assumed to occur at a similar level of voltage given the overlap in the confidence intervals of all samples. The closeness of the calculated average values of breakdown voltage as well as the overlapping 95% confidence intervals support pooling of the sample averages to allow for CPF analysis to be performed on the data.

The average time to breakdown of each of the three mineral oil samples is shown in Figure 5-25b, where it can be assumed that statistical difference may not exist, at the selected degree of confidence, between samples in the calculated averages. Unlike breakdown voltage data, the longest average time to breakdown is calculated for Sample 1 (2203ns) with the lowest average value associated with Sample 2 (2098ns). This can be attributed to the larger spread of the experimental data for the time to breakdown parameter, as compared with that of breakdown voltage apparent when the error bars of Sample 2 and 3 are compared. Given the likelihood of the lack of statistical difference in the calculated average values of time to breakdown it is reasonable to group this data and for it to be used in CPF analysis.

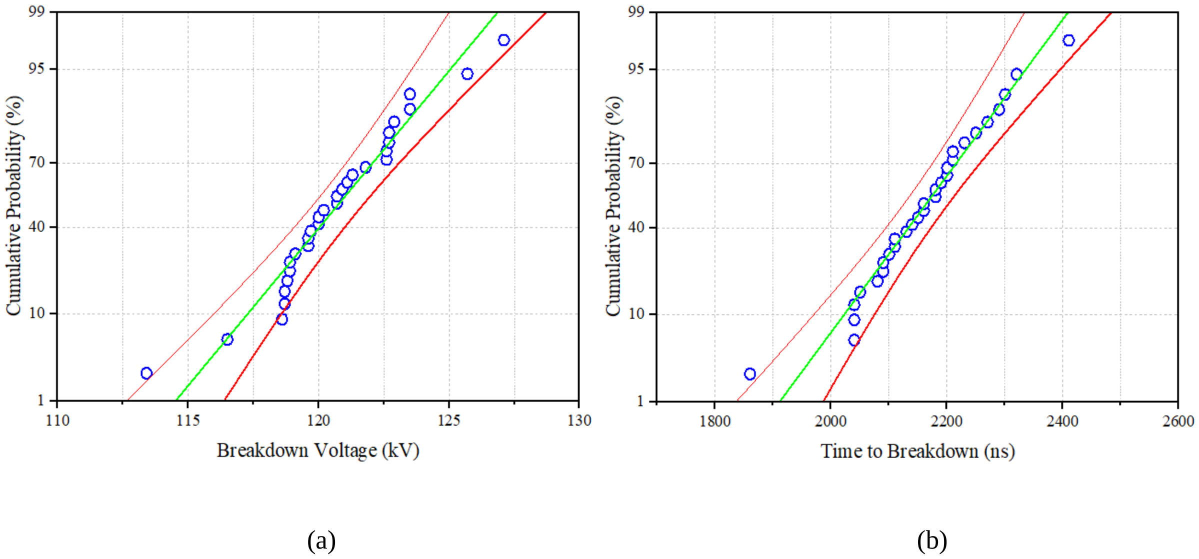


(a) (b)

Figure 5-26; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown of the ‘Elevated humidity’ mineral oil when stressed with negative microsecond impulse is provided in Figure 5-26a. Given the overlap in the 95% confidence intervals there may be no statistically significant difference in the level of voltage required to cause breakdown of any of the samples when under positive microsecond impulse stress. The likely statistical similarity in breakdown voltage that exists between all samples supports that the data can be pooled into one single dataset.

Time to breakdown data (Figure 5-26b) shows identical behaviour to that of breakdown voltage, with the three samples assumed, based on the overlapping confidence intervals, to require a statistically similar time for breakdown to occur. Interestingly even though Sample 2 and Sample 3 have the same average breakdown voltage (139kV) there exists a 6% difference in the calculated average time to breakdown, with Sample 3 shown to require a longer time than Sample 2. The discrepancy in breakdown voltage and time to breakdown data is again assumed, due to the comparable size of the confidence intervals, to be due to slight distortions in the experimental waveform originating from parasitic capacitance and inductance; as was the case with the 'As Received' and 'Ambient humidity' condition natural ester (discussed in Section 5.2.1.3 and 5.2.2.3 respectively).



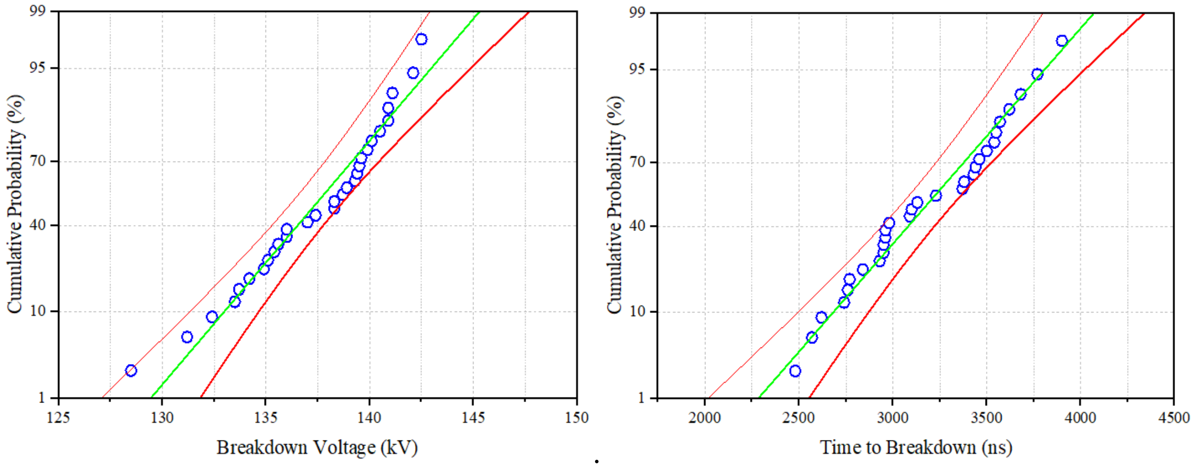
(a)

(b)

Figure 5-27; *Probability plots for 'Elevated humidity' mineral oil; CPFs for positive 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF associated with the breakdown of the 'Elevated humidity' mineral oil under positive microsecond impulse has been given above. From Figure 5-27a it can be seen that the experimental data is in good agreement with the predicted distribution line, with all but one data point contained within the confidence banding. The slight deviation of the data from the distribution reference is not surprising given that the data obtained a p-value of 0.48 from the KS normality test. From the CPF the levels of voltage which correspond to a probability of breakdown of 10%, 50% and 95% are predicted to be 117kV, 121kV and 125kV respectively.

The associated time to breakdown data was also shown by the KS normality test to be distributed normally (p-value ~1). Due to this nearly perfect p-value, it is not surprising that the data, shown in Figure 5-27b, resides almost exclusively on the distribution reference line. Mild deviation is observed at the uppermost and lowermost percentiles with one data point seen to sit outside the confidence bands. The predicted values of time to breakdown resulting in a 10%, 50% and 95% probability of breakdown have been taken from the CPF, with these shown to be 2023ns, 2160ns, and 2335ns respectively



(a) (b)

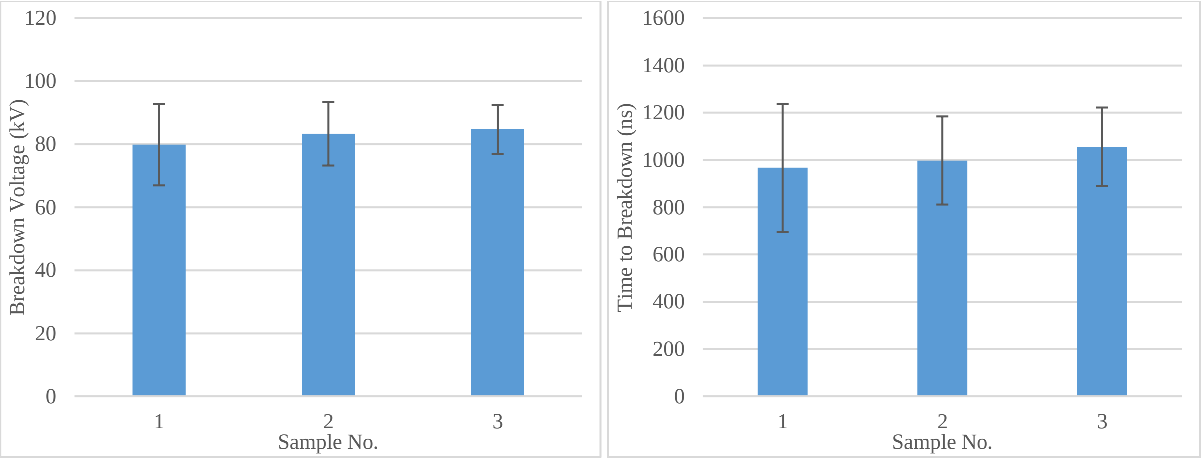
Figure 5-28; *Probability plots for 'Elevated humidity' mineral oil; CPFs for negative 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

Figure 5-28a shows the CPF produced from the breakdown voltage data obtained from the stressing of the ‘Elevated humidity’ mineral oil with microsecond impulses of negative polarity. Despite the mild deviation of the experimental data points from the distribution reference line, the data was still confirmed to follow a normal distribution (p-value 0.55). Predicted values of voltage that will cause a 10%, 50% and 95% likelihood of breakdown of the mineral oil were extracted from the CPF, with these shown to be 133kV, 137kV and 143kV respectively.

The time to breakdown of the mineral oil in the ‘Elevated humidity’ state when under negative microsecond impulse stress was confirmed to be normally distributed (p-value 0.69). The distribution of the data is in good agreement with the predicted distribution reference line with all data points residing on or close to this line. It is evident from the CPF (Figure 5-28b) that 20% of the recorded breakdowns required a similar time to breakdown (~3000ns). While this was not observed in the breakdown voltage data it can be assumed that this results from small changes in the impulse waveform from test-to-test producing a different voltage for a given time. From the CPF the predicted amount of time required to cause breakdown of the fluid at all percentiles of interest was extracted; with these times shown to be 2684ns (10th), 3176 (50th) and 3807ns (95th).

5.2.3.2. Breakdown of synthetic ester in the 'Elevated humidity' condition

Review of the breakdown data obtained during the testing of the synthetic ester under microsecond impulse stress confirmed that no upward or downward trend existed in the breakdown voltage or time to breakdown of the three liquid samples for either impulse polarity. The lack of any clear trend in the experimental data allowed for the grouping of the ten separate breakdowns experienced by each sample into six discrete datasets, three per impulse polarity, for the purpose of mean value analysis.



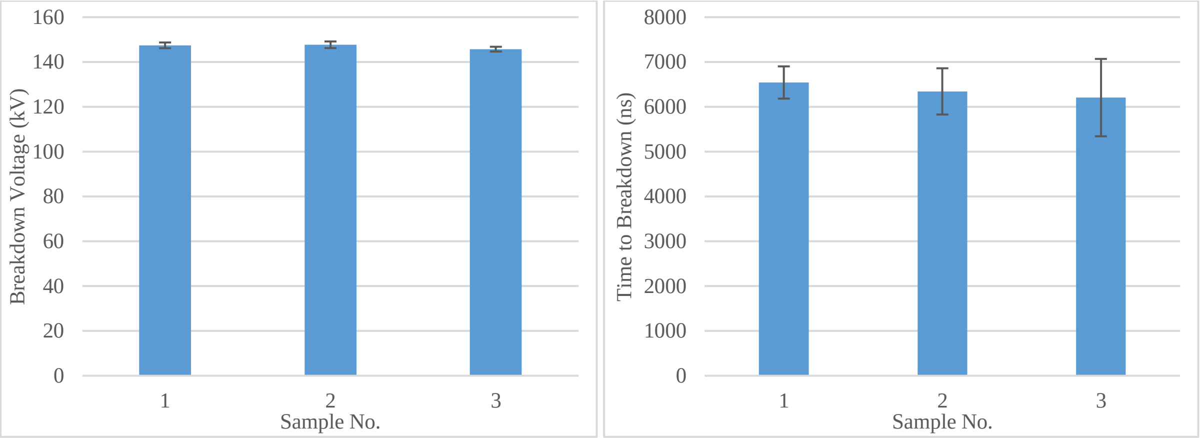
(a) (b)

Figure 5-29; *Positive 7μs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages calculated for each of the three 'Elevated humidity' synthetic ester samples when stressed with microsecond impulse of positive polarity have been given above (Figure 5-

29a). From the figure it can be assumed that all three samples are likely to require a statistically similar level of voltage to cause breakdown of the fluid. Breakdown of the fluid was shown to take place over a narrow range of values with only a 3% difference in the sample-to-sample averages; though as aforementioned all samples are likely to have a statistically similar dielectric strength given the overlapping 95% confidence intervals. This also allows for the grouping of the experimental data into one large dataset for the purpose of CPF analysis.

The average time to breakdown of each of the synthetic ester samples shows a probable lack of statistical difference in the time required to result in breakdown of the fluid. From Figure 5-29b it is clear that the same behaviour is seen in time to breakdown as was observed in breakdown voltage; with Sample 3 requiring the longest time to breakdown (1056ns) and Sample 1 the shortest (967ns). That said, a slightly larger difference in the time to breakdown averages is observed than was the case with breakdown voltage (~8% as compared with 3%). This can be attributed to the wider spread of the time to breakdown data associated with the samples, clearly evident with the much larger error bars present in this data.

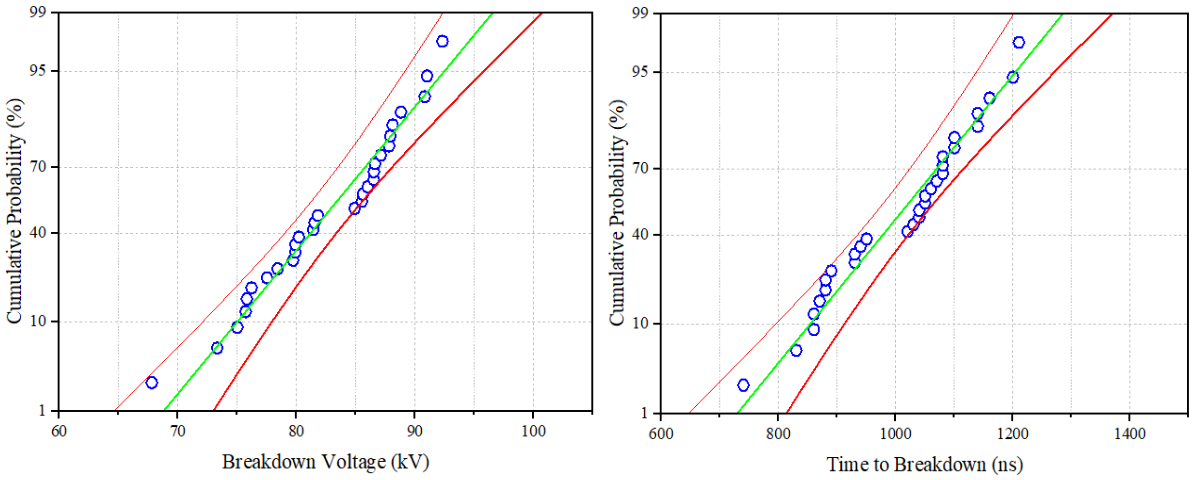


(a) (b)

Figure 5-30; *Negative 7μs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages of the ‘Elevated humidity’ synthetic ester samples when exposed to negative polarity microsecond impulse are shown in Figure 5-30a. From the data presented it can be said that all three samples are likely to have a similar breakdown strength, with only a ~1% difference in the calculated sample averages. Although as the 95% confidence intervals overlap all three samples can be assumed to exhibit the same, statistically similar, breakdown strength.

The average time to breakdown calculated for the three ‘Elevated humidity’ synthetic ester samples when under negative microsecond impulse stress are given above (Figure 5-30b). As with breakdown voltage, statistical difference may not exist between the three calculated values at the selected degree of confidence. However, unlike the average values of breakdown voltage, the highest average time to breakdown was calculated for Sample 1 (6543ns), rather than Sample 2 (6344ns), with the lowest values still associated with Sample 3 (6206ns). This discrepancy can be attributed to the breakdown of the synthetic ester taking place near the nominal peak of the voltage impulse where for a small change in voltage there is a large change in time. Furthermore, the time to breakdown values are also spread over a larger range of values than the breakdown voltage; demonstrated by the much larger error bars present in Figure 5-30b.

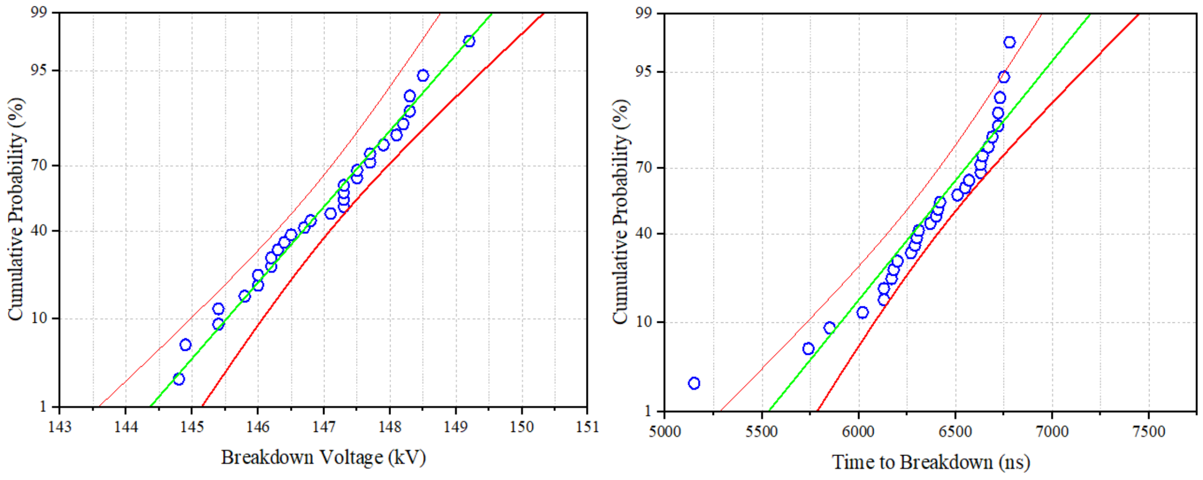


(a) (b)

Figure 5-31; *Probability plots for 'Elevated humidity' synthetic ester; CPFs for positive 7µs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data measured during the testing on the ‘Elevated humidity’ synthetic ester under positive microsecond impulse stress can be seen in Figure 5-31a. The data was confirmed to be of normal distribution by the KS normality test (p-value 0.47). Despite the p-value being below 0.5 the data is still in good agreement with the distribution reference line with the majority of data points (77%) residing on or close to the line and all data contained within the 95% confidence banding. From the CPF given in Figure 5-31a the breakdown voltages predicted to result in a 10%, 50% and 95% probability of breakdown were taken to be 75kV, 83kV and 93kV respectively.

The conformance of the time to breakdown data to a normal distribution was also assured through the KS normality test with the data returning a p-value of 0.53. Again, experimental data shows good agreement with the distribution reference, with almost all data contained inside the confidence bands and the vast majority (90%) residing on or close to the reference line. The predicted values of time to breakdown at the percentiles of interest are shown to be 854ns (10th), 1007ns (50th) and 1204ns (95th).



(a) (b)

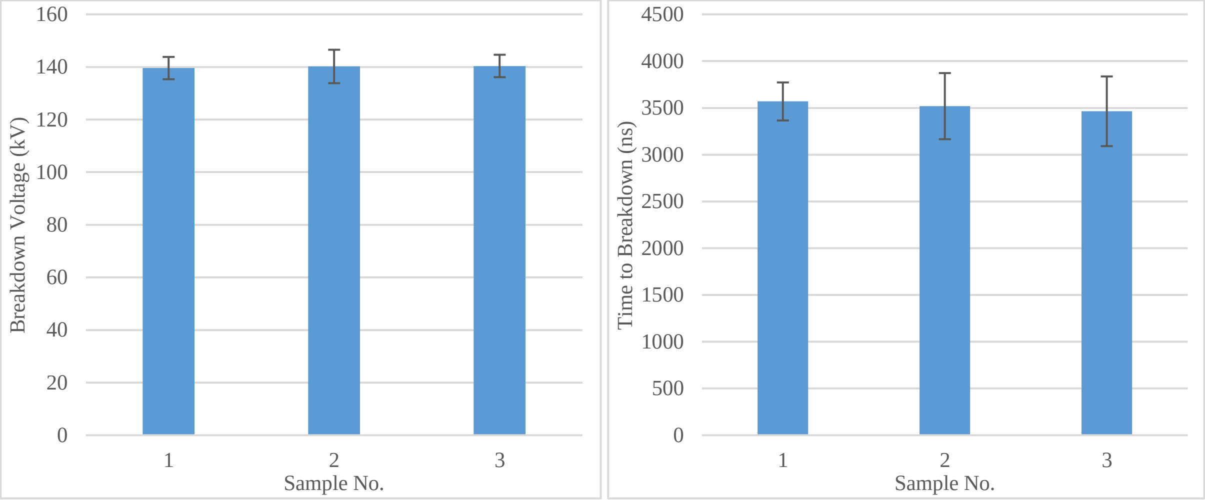
Figure 5-32; *Probability plots for 'Elevated humidity' synthetic ester; CPFs for negative 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from the data on breakdown voltage gathered during the stressing of the ‘Elevated humidity’ synthetic ester with microsecond impulses of negative polarity has been provided above (Figure 5-32a). The data was shown by the KS test to be of normal distribution (p-value 0.76). Given the high goodness of fit coefficient (p-value), it is of no surprise that the experimental data is in excellent agreement with the distribution reference line. As can be seen from the figure all data sits within the confidence bands and resides close to the reference line. From the CPF the levels of voltage predicted to cause a 10%, 50% and 95% probability of breakdown were 146kV, 147kV and 149kV respectively.

The distribution of the time to breakdown data was confirmed as being normal, with the data returning a p-value of 0.75. Given that the data has such a high goodness of fit coefficient it is surprising that not all data points reside within the confidence bands. As can be seen from Figure 5-32b two data points at the uppermost and lowermost percentiles sit outside the confidence bands. That said these are clear outliers, with the rest of the data points sitting on or close to the distribution reference line. From the CPF the times that correspond to a probability of breakdown of 10%, 50% and 95% have be extracted, with these shown to be 5906ns, 6364ns and 6952ns respectively.

5.2.3.3. Breakdown of natural ester in the 'Elevated humidity' condition

Analysis of the experimental data obtained for the 'Elevated humidity' natural ester when stressed with positive and negative microsecond impulses showed that no discernible trend exists in either the breakdown voltage or time to breakdown; with both increases and decreases in both breakdown parameters observed across the dataset of each sample. Therefore, the decision was taken to group each set of 10 shots into six discrete datasets, one per liquid sample and three for a given impulse polarity, to allow for mean value analysis.

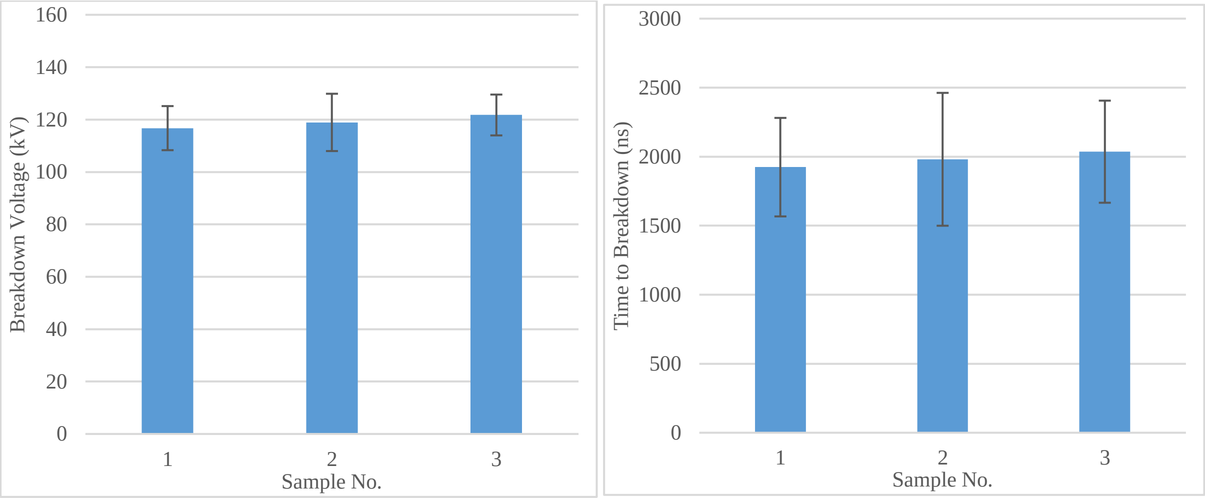


(a) (b)

Figure 5-33; *Positive 7μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average values of breakdown voltage calculated for each of the three ‘Elevated humidity’ natural ester samples obtained when the fluid was stressed with the positive microsecond impulse are shown in Figure 5-33a. Interestingly there is no difference in the average values of breakdown voltage calculated, with each sample returning a value of 140kV. Therefore, it is not surprising that statistical difference may not exist between the breakdown voltages of each sample.

When the average values of time to breakdown are examined (Figure 5-33b), again statistical difference between the samples may not be present at the selected degree of confidence. However, unlike the breakdown voltage, a 3% difference exists in the highest (3569ns) and lowest (3464ns) average values of time to breakdown, calculated for Sample 1 and Sample 3 respectively. This presence of a difference in average values of time to breakdown, where none exists in breakdown voltage, can be attributed to a wider spread of the data obtained for specific samples, which can be seen in the varying size of the sample confidence intervals. This increased spread is likely to result from slight distortions in the impulse waveform that can cause different values of voltage to be measured for the same delay time (time to breakdown).

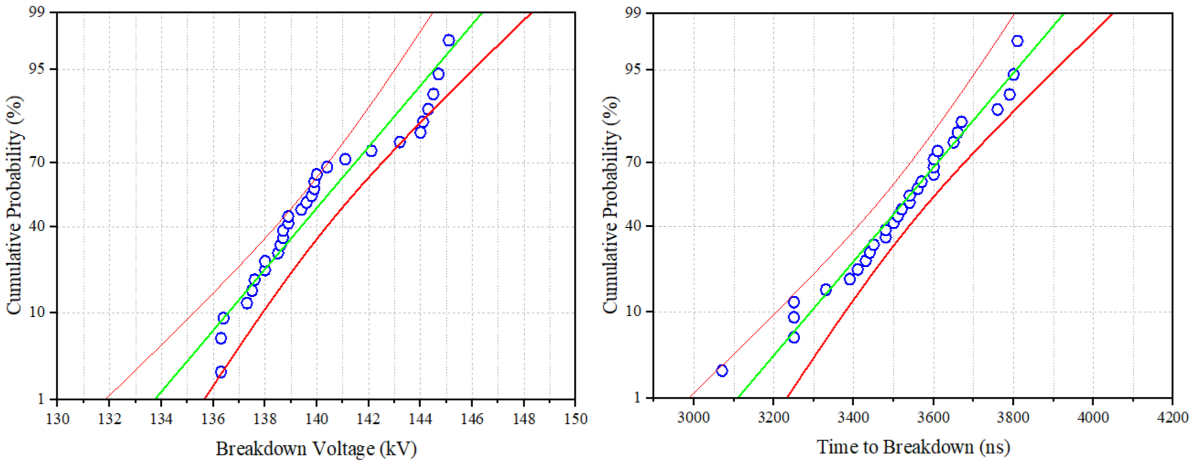


(a) (b)

Figure 5-34; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage for each of the three 'Elevated humidity' natural ester samples when exposed to microsecond impulses of negative polarity are shown in Figure 5-34a. From the figure it is evident that the 95% confidence intervals for all three samples exhibit overlapping and thus a statistically similar dielectric strength may be assumed for all samples. As before this likely lack of statistical difference between samples has allowed the data to be pooled into one large dataset (n = 30) for the purpose of CPF analysis.

The calculated values of time to breakdown for each of the three natural ester samples when placed under negative microsecond impulse stress can be seen in Figure 5-34b. As with breakdown voltage, all three samples can be said, given the overlap in the confidence intervals, to be likely of requiring a statistically similar time to breakdown. There is however a greater difference in the average time to breakdown of each sample than exists in the average values of breakdown voltage (6% as compared with ~4%) which is attributed to the greater spread of the time to breakdown data; confirmed by the much larger error bars associated with the time to breakdown data.

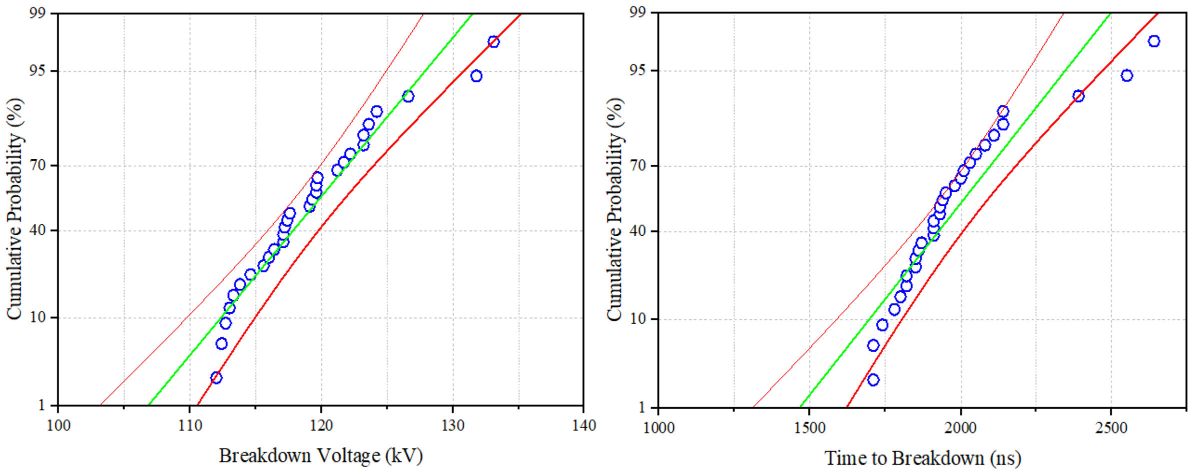


(a) (b)

Figure 5-35; *Probability plots for 'Elevated humidity' natural ester; CPFs for positive 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

Figure 5-35a shows the CPF produced from the experimental breakdown voltage data gathered from the stressing of the 'Elevated humidity' natural ester with microsecond impulses of positive polarity. The data was confirmed by the KS normality test to follow a normal distribution (p-value 0.28). Given this relatively low goodness of fit coefficient it is not surprising that a number of experimental data points deviate from the distribution reference line, particularity those in the upper percentile range (>70th). Despite the low p-value all data is contained within the confidence bands with 70% of the data residing on or close to the distribution line. From the CPF the voltages corresponding to a 10%, 50% and 95% probability of breakdown have been extracted, with these predicted to be 137kV, 140kV and 145kV respectively.

The experimental data on the time to breakdown of the 'Elevated humidity' natural ester when under positive microsecond impulse stress was used to create the CPF shown in Figure 5-35b. The data was subjected to the KS normality test and was confirmed to be distributed normally (p-value ~1). With the data returning a near perfect goodness of fit coefficient, it is interesting that some data points deviate from the distribution reference line at both the uppermost and lowermost percentiles. Nevertheless, the data is in excellent agreement with the distribution reference line with ~90% of the experimental data points siting on the line. The time to breakdown values that will result in a 10%, 50% and 95% probability of breakdown were shown by the CPF to be 3292ns, 3517ns and 3806ns respectively.



(a) (b)

Figure 5-36; *Probability plots for 'Elevated humidity' natural ester; CPFs for negative 7μs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained during the testing of the 'Elevated humidity' natural ester when under negative polarity microsecond impulse was confirmed to be normally distributed (p-value 0.72).

As can be seen from the CPF (Figure 5-36a) all but one data point is contained within the 95% confidence banding and 80% of the data sits on or close to the distribution reference line; unsurprising given the high goodness of fit coefficient. From the CPF above the levels of voltage that correspond to a probability of breakdown of 10%, 50% and 95% were predicted to be 112kV, 119kV and 128kV respectively.

The CPF plot generated from the experimental time to breakdown data is shown in Figure 5-36b. Conformance of the experimental data to a normal distribution was assured with the KS normality test with the data returning a goodness of fit coefficient of 0.43. Given the data produced such a p-value it is not surprising that the data shows deviation from the distribution reference line with this observed both for the percentiles >80th and those <10th. That said the data between these extremes shows good conformance with the distribution reference line. From the CPF it was possible to obtain the values of time to breakdown that will result in a 10%, 50% and 95% probability of liquid breakdown (1696ns, 1980ns and 2345ns respectively).

5.2.3.4. Summary of breakdown of dielectric liquids in the ‘Elevated humidity’ condition

Samples of the three dielectric liquids in the ‘Elevated humidity’ condition were stressed with microsecond impulses of both positive and negative polarity. Experimental data obtained for each sample of the dielectric fluids was evaluated and no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, was observed; irrespective of energisation polarity. This allowed for the pooling of sample data into three discrete datasets for each of the three liquids to be used in mean value analysis. Analysis of this data demonstrated that statistical difference may not exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the three discrete datasets into a larger pool for the means of cumulative probability analysis. Calculated values of the chosen breakdown parameters (breakdown voltage and time to breakdown) derived from both the mean and CPF analysis have been summarised in Table 5-3.

Table 5-3; *Average breakdown voltage and time to breakdown of the 'Elevated humidity' dielectric fluids when stressed with 7μs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	121 ± 4.5kV	117kV	125kV	0.48
	MIDEL 7131	83 ± 10.1kV	75kV	92kV	0.47
	Envirotemp FR3	140 ± 4.6kV	137kV	145kV	0.28
Negative impulse	Shell Diala S4	137 ± 5.8kV	133kV	143kV	0.55
	MIDEL 7131	147 ± 1.9kV	145kV	149kV	0.76
	Envirotemp FR3	119 ± 9kV	112kV	128kV	~1
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	2160 ± 182ns	2023ns	2335ns	~1
	MIDEL 7131	1007 ± 203ns	854ns	1204ns	0.53
	Envirotemp FR3	3517 ± 298ns	3292ns	3806ns	0.72
Negative impulse	Shell Diala S4	3176 ± 652ns	2684ns	3807ns	0.69
	MIDEL 7131	6364 ± 608ns	5906ns	6952ns	0.75
	Envirotemp FR3	1980 ± 377ns	1696ns	2345ns	0.43

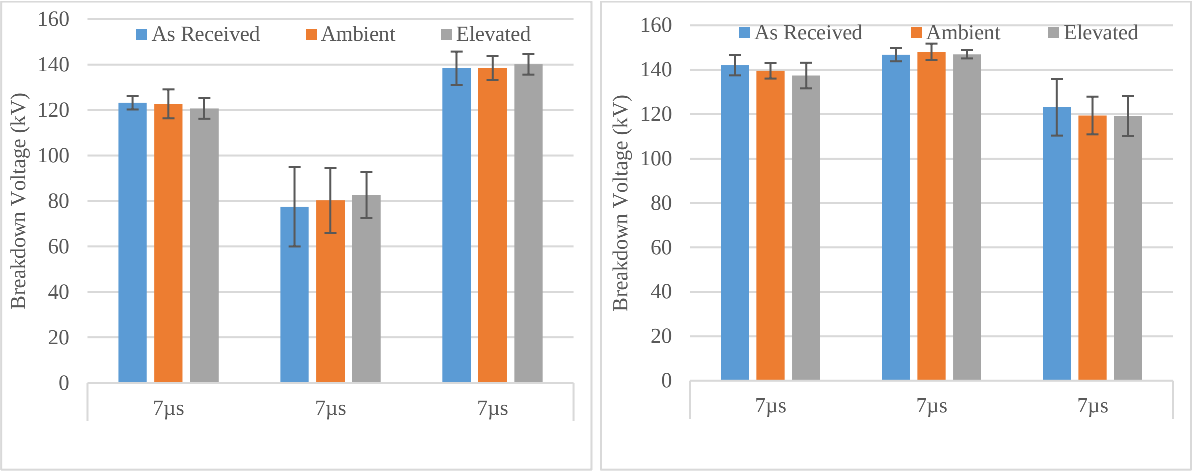
Evaluation of the experimental data gathered from the stressing of the three ‘Elevated humidity’ liquids with positive microsecond impulse has shown that statistical difference is present in the level of voltage necessary to cause liquid breakdown. The natural ester was shown to have the best dielectric strength, 16% higher that of the mineral oil and 67% greater than the synthetic ester, when under positive impulse stress. This is also reflected in the time to breakdown data, which shows that the natural ester requires ~63% longer to breakdown than the mineral oil and over 3.5 times that of the synthetic ester fluid. Analysis of the breakdown of the liquids when exposed to negative microsecond impulse shows opposing behaviour to that observed from the positive polarity breakdown. The synthetic ester now exhibits the highest dielectric strength and the natural ester the lowest. Statistical difference still exists between the breakdown voltages of all three fluids, with the synthetic ester requiring voltages 7% and 24% higher to result in fluid breakdown than the mineral oil and natural ester respectively. The time to breakdown obtained for the three fluids under negative microsecond impulse shows identical behaviour to that of the breakdown voltage, with the synthetic ester requiring a statistically longer time to breakdown that both the mineral oil and the natural ester. The time to breakdown of the synthetic ester under the negative impulse conditions is twice that of the mineral oil and nearly 3.2 times that of the natural ester fluid.

Under positive microsecond impulse, the CPF predicts that the natural ester fluid requires a higher level of breakdown voltage at all percentiles of interest; ~16% greater than the mineral oil and 58-83% higher than the synthetic ester. The breakdown of the synthetic ester is predicted to occur over the widest range of values; attributed to the experimental breakdown of both the mineral oil and natural ester occurring at a point on the energising impulse where the change in voltage is much slower. When the impulse is negative opposite behaviour of the fluids is predicted by the CPF to that under positive energisation. Breakdown of the synthetic ester is now higher at all percentiles of interest with breakdown predicted to be a much as 9% higher than that of the mineral oil and 29% above that of the natural ester. The range of predicted values of breakdown voltage is now the narrowest for the synthetic ester and the widest for the natural ester, which again is the inverse to the predictions made by the CPF when the impulse is of positive polarity.

The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow an identical trend to that predicted for the breakdown voltage, with the natural ester shown to require the longest time to breakdown of all three dielectric liquids at all percentiles of interests and the synthetic ester the shortest. The spread of predicted values is largest in the data associated with the breakdown of the natural ester, with the breakdown of the mineral oil predicted to occur over the narrowest range. The longest values of time to breakdown when under negative voltage stress are predicted, as with breakdown voltage, for the synthetic ester while the natural the shortest. The range of predicted times at which the breakdown of the mineral oil will occur now span the widest range, with those associated with the natural ester the narrowest. This is in contrast to the predictions made with the experimental data obtained under positive impulse stress where the time to breakdown of the natural ester fluid spanned the widest range of predicted values and the mineral oil the narrowest.

5.3. Summary of breakdown under 7µs rise-time impulse

This chapter has presented the results of experiments conducted involving the three chosen dielectric liquids (Shell Diala S4 mineral oil, MIDEL 7131 synthetic ester and Envirotemp FR3 natural ester) in three discrete states of relative humidity (‘As Received’, ‘Ambient humidity’ and ‘Elevated humidity’). Three samples of each of the chosen liquids in the given states of relative humidity were stressed with the so called ‘microsecond impulse’ (nominal rise-time 7µs) of both positive and negative polarity. The samples were exposed to ten separate breakdown events with breakdown voltage and time to breakdown recorded. This data was then subjected to both mean value and cumulative probability analysis.



(a) (b)

Figure 5-37; *(a) Positive and (b) negative 7µs impulse breakdown voltage of the mineral oil, synthetic ester and natural ester in the three discrete levels of relative humidity. Each column is the mean of thirty individual breakdown events, with error bars showing 95% confidence intervals.*

Statistical analysis of the measurements gathered during breakdown experimentation demonstrates that a statically significant variation in breakdown voltage of the examined dielectric fluid may not exist, at the selected degree of confidence, as relative moisture content is increased irrespective of impulse polarity; evident in Figure 5-37a and 5-37b. Demonstrating that, given the specific electrode configuration implemented during experimentation, the dominant mechanism influencing breakdown is that of ionisation front (streamer) development; shown to be governed by applied electric field, electrode topology and resultant space charge development [35]. In such ionisation driven processes moisture has a diminished influence over breakdown. It must however be said that the presence of water molecules within the dielectric fluid will still result in distortions to, and enhancement of, the electric field due to ionisation of the molecules and changes in the electronegativity of the fluid. This process may be coupled with an increase in joule heating of the liquid. As such a heating process is highly deterministic, it can be said that it would reduce the unpredictability of the streamer breakdown process resulting in a reduction in the variability of breakdown voltage.

When evaluating how impulse polarity can affect the breakdown characteristics of the chosen insulting liquids an obvious sensitivity to polarity of applied voltage exists; with the ester liquids exhibiting conflicting behaviours for a given voltage polarity. When exposed to a positive HV tip the natural ester Envirotemp FR3 has the highest dielectric strength, ~16% above the mineral oil under investigation; with the synthetic ester MIDEL 7131 performed significantly worse than both the natural ester Envirotemp FR3 and mineral oil Shell Diala S4; with breakdown voltage ~41% & ~31% lower respectively. This is attributed to a reduction in the positive breakdown strength experienced by the MIDEL 7131 ester after the first breakdown event of a new liquid sample (regardless of the moisture content). Further investigation is required to fully understand this reduction of positive breakdown voltage in MIDEL 7131 after the first breakdown event. Under negative energisation, inverse results to those of the positive polarity tests were observed; with the synthetic ester MIDEL 7131 performing considerably better than both the natural ester Envirotemp FR3 and mineral oil Shell Diala S4. Recorded values of breakdown voltage for the synthetic ester were ~23% and ~7% greater than those measured for the natural ester and mineral oil respectively. The dielectric behaviour of both the synthetic ester and mineral oil under negative impulse is typical of that described in literature; with breakdown strength under negative voltage higher than when a positive voltage is applied [18], [86], [129], [137]. This however cannot be said for the investigated natural ester; with positive breakdown voltage for Envirotemp FR3 ~18% higher than when under negative impulse stress. [138] reports similar results to those observed within this experimental work. Within the work discussed in [138] a number of configurations of electrodes are utilised to obtain the impulse breakdown characteristics of a collection of insulating fluids. The authors report comparable behaviour for Envirotemp FR3 to that observed within this work; i.e. breakdown voltage is higher when the impulse is positive. Similar results to that of [138], which show the positive breakdown voltage of an insulating fluid to be higher than the negative breakdown voltage, have been reported in literature [139]-[144]; however, these behaviours are commonly observed in well-defined liquids such as hexane, chlorobenzene and n-octane. In [143] positive breakdown voltage of both cyclohexane and benzene is shown to be higher than when the same liquids were exposed to negative impulse. The authors suggest that this behaviour is determined by the molecular structure of the fluid; particularly the presence of chlorine and fluorine atoms. Such atoms alter the electron affinity of the fluid which can encourage the development of negative streamers [143]. Similar sensitivity of breakdown voltage to the molecular structure of the fluid can be found in [144], where again the positive breakdown voltage is superior to negative. The presence of F atoms within the molecular structure of Perfluoropolyether fluid is accredited as the cause of the aforementioned polarity sensitivity in breakdown voltage; due to the high electron affinity of F atoms [144]. Such high electronegativity may explain the clear favourability of negative polarity breakdown in the case of the natural ester Envirotemp FR3. This allows the removal of energetic electrons from the system leading to the formation of negative ions with a low mobility as compared with electronic mobility, [139], 143], [144]. In [139] the authors suggest that the difference in the development of space charge in the gap when more mobile electrons are replaced by less mobile negative ions causes the breakdown strength under negative energisation to approach that under positive energisation. To fully substantiate this however additional information relating to the specific composition of the natural ester is required. In [145] a brief description is given of the formula used to manufacture Envirotemp FR3, however no clear details are given as to the specific additives used just an acknowledgement of their presence and concentration (5%vol). Consequently, no clear conclusions can be drawn at this time as to the mechanisms driving this polarity dependency in the breakdown voltage of the examined natural ester.

Table 5-4; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under positive 7µs impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	2247 ± 295ns	3.6km/s	4.1km/s	3.2km/s	2nd
	MIDEL 7131	943 ± 324ns	8.5km/s	12.9km/s	6.3km/s	2nd/3rd
	Envirotemp FR3	3403 ± 334ns	2.4km/s	2.6km/s	2.1km/s	2nd
Ambient humidity	Shell Diala S4	2368 ± 461ns	3.4km/s	4.2km/s	2.8km/s	2nd
	MIDEL 7131	963 ± 248ns	8.3km/s	11.1km/s	6.6km/s	2nd/3rd
	Envirotemp FR3	3422 ± 338ns	2.3km/s	2.6km/s	2.1km/s	2nd
Elevated humidity	Shell Diala S4	2160 ± 182ns	3.7km/s	4km/s	3.4km/s	2nd
	MIDEL 7131	1007 ± 203ns	7.9km/s	10km/s	6.6km/s	2nd/3rd
	Envirotemp FR3	3517 ± 298ns	2.3km/s	2.5km/s	2.1km/s	2nd

Table 5-5; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under negative 7µs impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	4192 ± 1226ns	1.9km/s	2.7km/s	1.5km/s	2nd
	MIDEL 7131	6653 ± 940ns	1.2km/s	1.4km/s	1.1km/s	2nd
	Envirotemp FR3	2224 ± 756ns	3.6km/s	5.5km/s	2.7km/s	2nd
Ambient humidity	Shell Diala S4	3547 ± 596ns	2.3km/s	2.7km/s	1.9km/s	2nd
	MIDEL 7131	6952 ± 722ns	1.2km/s	1.3km/s	1km/s	2nd
	Envirotemp FR3	2012 ± 350ns	4km/s	4.8km/s	3.4km/s	2nd
Elevated humidity	Shell Diala S4	3176 ± 652ns	2.5km/s	3.2km/s	2.1km/s	2nd
	MIDEL 7131	6364 ± 608ns	1.3km/s	1.4km/s	1.2km/s	2nd
	Envirotemp FR3	1980 ± 377ns	4km/s	4.9km/s	3.5km/s	2nd

The average time to breakdown of the three dielectric liquids in each state of relative humidity when stressed positive microsecond impulse are shown in Table 5-4. Information on the minimum average propagation velocity of breakdown streamers is also provided (calculated by dividing the inter-electrode gap distance by the average time to breakdown) as well as the upper and lower average velocities which are derived from the upper and lower average time to breakdown values. As no account has been taken of the statistical time (time for onset of the streamer), the velocities stated herein can be thought of as the minimum average velocities at which the streamer propagates through the gap. Under positive voltage stress there is unlikely to be a statistical difference in average time to breakdown for a given liquid as the relative humidity of the fluid is increased. However, statistical difference does exist between liquids, with the natural ester exhibiting the longest time to breakdown at all investigated humidity levels. Despite this, all liquids exhibit similar streamer velocities. From the data provided it has been shown that the average velocities characteristic of 2nd mode streamers are predominately observed in the fluids under positive microsecond impulse stress, though some early-stage 3rd mode streamer development is associated with the breakdown of the synthetic ester MIDEL 7131. It can be said that at all levels of relative humidity streamers in natural ester propagate slower than those in both the mineral oil and synthetic ester fluid. Given that only ‘slow’ 2nd mode streamers are shown to occur under the microsecond impulse it can be assumed that the breakdown mechanism has been altered from that driving the breakdown under lightning impulse. It is postulated that under the slower microsecond impulse the breakdown mechanism behaves more like the process of electrostriction (bubble formation) than complete ionisation front breakdown. This may explain why the natural ester exhibits the longest time to breakdown as the amount of energy required to create a low-density region (bubble) is greater in this fluid compared to both the mineral oil and synthetic ester fluid, which possess both lower viscosity and boiling points than the natural ester.

Table 5-5 provides the average time to breakdown data gathered from stressing the liquids with negative polarity microsecond impulse. Evaluation of this data delivers contrasting results to that of Table 5-4 in that at all levels of relative humidity the synthetic ester requires a statistically longer average time to breakdown than both the mineral oil and natural ester. Relative humidity of the fluid is, as with positive breakdown, shown to exert a negligible influence on breakdown performance of the liquids with statistical difference in the time to breakdown of a given dielectric liquid as relative humidity is increased unlikely to exist. Streamer velocity under negative energisation is considerably lower for each of the dielectric liquids than when under positive voltage stress. This is as a consequence of the streamer development process under negative energisation and the mitigating effect of the negative space charge in the region surrounding the HV electrode and subsequently the streamer head. The streamers developed in the synthetic ester under negative microsecond impulse are shown to propagate at the slowest velocities observed during experimentation. Velocities of as low as 1km/s are calculated for streamers in the synthetic ester at all states of relative humidity; this is in contrast to what was observed under positive voltage stress where the synthetic ester harboured the highest streamer velocities. This change in behaviour is a due to the aforementioned drop in the breakdown voltage, and subsequently the time to breakdown, of the synthetic ester which occurred after the initial breakdown of the fluid. The cause of this reduction in dielectric strength is not fully understood at this time and thus requires further investigation. It can however be said that it is not as a result of the presence of bubbles within the fluid, nor the condition of the electrodes. A similar drop in breakdown voltage after the initial breakdown of a dielectric has been reported previously [146], though this was observed in the breakdown of gas, where the effect was attributed to a build-up of charge within the gas after the first breakdown shot. This however is not thought to be the cause of the observations made in this thesis as adequate time (5mins) was given between breakdowns of the fluid to ensure any residual charge would dissipate.

In conclusion, this chapter has shown that under microsecond impulse the dielectric liquids exhibit contrasting breakdown behaviour depending on the polarity of applied HV impulse. When the HV impulse is of positive polarity, the natural ester is seen to have the best breakdown performance, above that of both the mineral oil and synthetic ester and even surpassing its own negative breakdown strength. When the impulse is negative, the natural ester now demonstrates the worst breakdown performance with the synthetic ester now outperforming both other fluids. Irrespectively of impulse polarity similar streamers as shown to be developed in all three liquids; with these tending to be of the ‘slower’ 2nd mode. That said streamers developed in the liquids under negative energisation, while still 2nd mode, are shown to propagate at a lower minimum average velocity in all liquids as compare with those developed from positive voltage stress. It can also be said that irrespective of energisation polarity the relative humidity of the fluid has no influence on either the breakdown voltage or time to breakdown of the examined mineral oil or ester fluids for the presented experimental conditions.

Chapter 6 – Breakdown of insulating fluids with impulses of 0.4μs rise-time

6.1. Introduction

This chapter is concerned with the bulk breakdown of the chosen dielectric fluids and further investigates the effect the rise-time of the impulse has on breakdown behaviour. The work presented and discussed focuses on experiments conducted using an impulse of considerable shorter rise-time than both the standard lightning impulse and microsecond impulse utilised for the work discuss in Chapter 4 and 5 respectively. The proceeding chapter is concerned with the presentation and discussion of experimental results gathered from breakdown tests conducted under impulse stress for which the nominal rise-time of the impulse was 0.4μs. As with the work discussed in the previous chapters (Chapter 4 and 5) both positive and negative impulses were utilised in order to ascertain the effect voltage polarity may have on the observed breakdown of mineral oil and ester fluids (natural and synthetic). The chosen liquids were tested in accordance with the methodology described in Section 3.6.1. Within this chapter the average breakdown voltage and time to breakdown for each of the liquid samples is presented along with the cumulative probability function for the entire dataset ($n = 30$) obtained for a given dielectric liquid. Firstly, experimental data will be presented and evaluated for similarity between the breakdowns of individual liquid samples of given dielectric fluid and relative humidity. Analysis of the mechanisms that may be responsible for the behaviours observed will be presented and discussed within the summary (Section 6.3) at the end of the chapter.

6.2. Experimental results

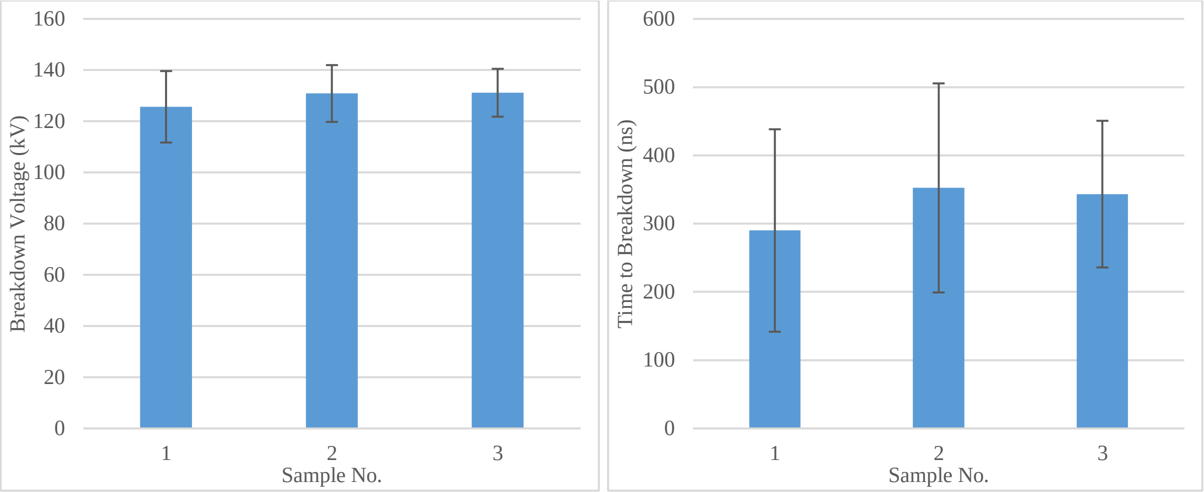
This section, and associated subsections, detail the experimental results obtained from stressing the liquid samples with impulses of considerably shorter rise-time, from hereafter referred to as the 'Nanosecond' impulse, than both the lightning impulse discussed in the Chapter 4 and the Microsecond impulse used in Chapter 5 (rise-time 0.4μs compared with 1.2μs and 7μs respectively). The effect voltage polarity may exert on the breakdown performance of the fluids was also evaluated with the use of both positive and negative impulses. The gathered experimental data was subdivided into groupings based on the three discrete levels of relative humidity of each liquid sample; discussed in detail in Section 3.3.1. One difference that exists in the experimental work involving the breakdown of the fluids under nanosecond impulse voltage was the requirement to increase the nominal peak impulse voltage from 150kV to 175kV for the testing of the mineral oil under negative impulse stress. This was necessary, as breakdown of the fluid could not be achieved with the impulses of 150kV peak amplitude.

6.2.1. Breakdown of liquid in 'As Received' condition

Within this section the data pertaining to the breakdown of the dielectric liquid samples in the 'As Received' condition is presented and discussed. Fluids in this condition are in the state as provided by the manufacturer. The only conditioning of the liquid samples was degassing prior to any breakdown tests, as discussing in Section 3.6.1. The relative humidity of liquid samples in the 'As Received' condition was 21%, 12.5% and 9% for the mineral oil, synthetic ester and natural ester respectively.

6.2.1.1. Breakdown of mineral oil in 'As Received' condition

The breakdown voltage and associated time to breakdown of the mineral oil samples in the 'As Received' condition (~21% relative humidity) are presented and discussed within this section. Analysis of the individual breakdowns of the mineral oil samples has shown that, irrespective of energisation polarity, there is no clear reduction, or increase, in breakdown voltage, or time to breakdown, when comparing the first and last (10th) breakdown in the test series. It is therefore possible to group the separate datasets, n = 10, (three for a given impulse polarity).

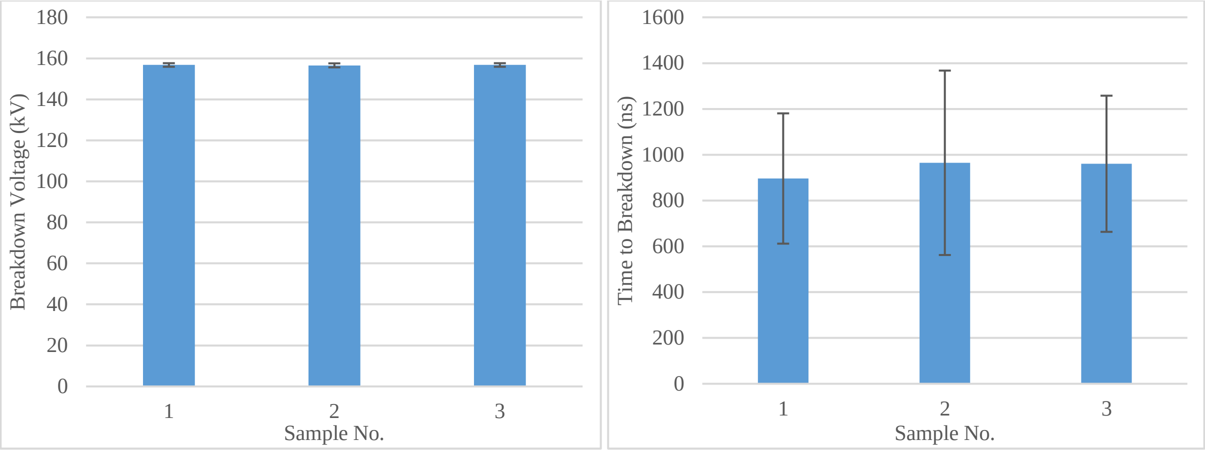


(a) (b)

Figure 6-1; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

From the data presented in Figure 6-1a it is clear that the confidence intervals associated with all three samples of 'As Received' condition mineral oil overlap and thus it can be assumed that all samples require a similar level of voltage to result in breakdown when the liquid is placed under positive nanosecond impulse stress. As these 95% confidence intervals overlap for all samples any numerical difference in average values is not likely to be of statistical significance.

Again, due to the overlapping of the confidence intervals, statistical difference may not exist between the calculated sample averages for the time to breakdown parameter. From the data in Figure 6-1b it can be seen that the average values of time to breakdown show slightly differing behaviour to that of the data in Figure 6-1a (average breakdown voltage), with Sample 2 (352ns), rather than Sample 3 (342ns), requiring the longest time to breakdown and Sample 1 the shortest (290ns). Given the closeness of the average breakdown voltages calculated for Sample 2 and Sample 3, 130kV and 131kV respectively, coupled with the fact that the average time to breakdown of each of the aforementioned samples is close to the nominal rise-time of the impulse (400ns), the discrepancy between breakdown voltage and time to breakdown can be explained by outliers within the dataset of Sample 2. This assumption is supported by the large confidence interval error bars associated with this sample.

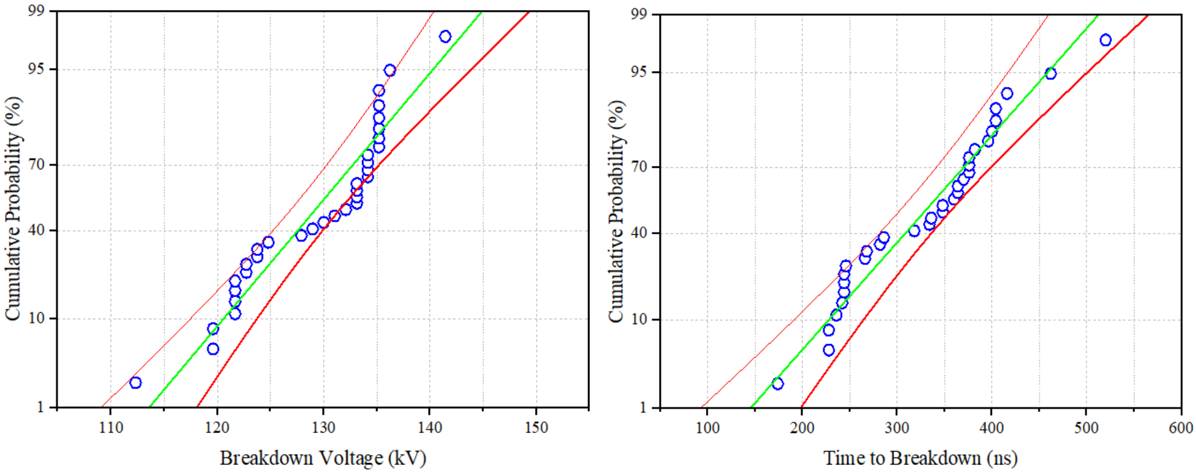


(a) (b)

Figure 6-2; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average values of breakdown voltage calculated for each of the three 'As Received' mineral oil samples obtained when the fluid was stress with negative nanosecond impulse are shown in Figure 6-2a. As aforementioned (Section 6.2), it was necessary to increase the nominal output voltage of the impulse circuit to achieve breakdown of this fluid under negative polarity nanosecond impulse. Even with this increase in the nominal peak amplitude of the voltage impulse breakdown of the mineral oil under negative nanosecond impulse consistently occurred on the plateau of the impulse (a point at which there is almost no change in voltage over an extended timescale). Consequently, there is no difference in the average values of breakdown voltage, with each sample returning a value of 157kV. It is therefore unsurprising that statistical difference is unlikely to exist between the breakdown voltages of each sample.

The average time to breakdown calculated for each 'As Received' sample of mineral oil when stressed with nanosecond impulses of negative polarity are shown above (Figure 6-2b). While identical averages were calculated for the of breakdown voltage of each (Figure 6-2a) there exists a 7% between the longest and shortest values of time to breakdown, derived for Sample 2 (965ns) and Sample 1 (896ns) respectively. This presence of a difference in average values of time to breakdown where none exists for breakdown voltage can be explained by breakdown of the fluid taking place on the plateau of the energising impulse where a minimal change in voltage will occur over a long timescale. Furthermore, it is clear that breakdown occurs at such a point on the impulse as the values of time to breakdown calculated for each sample are more than twice the nominal rise-time of the impulse (400ns).

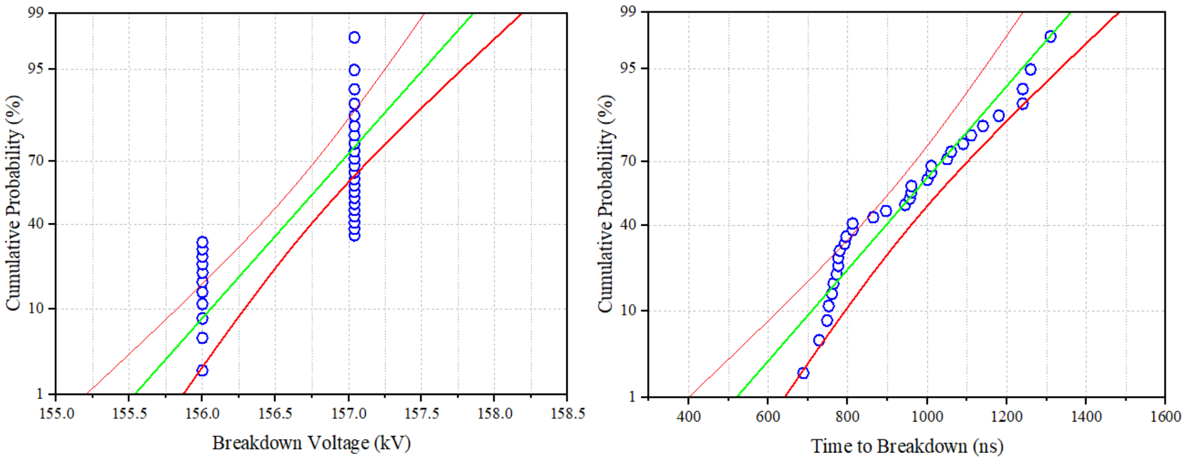


(a) (b)

Figure 6-3; *Probability plots for 'As Received' mineral oil; CPFs for positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage CPF generated from the data obtained during the stressing of the ‘As Received’ samples of mineral oil with positive polarity nanosecond impulse has been provided above (Figure 6-3a). The adherence of the data to a normal distribution was confirmed using the KS normality test, with the data returning a goodness of fit coefficient (p-value) of 0.12. Given this p-value, it is not surprising that the data deviates from the distribution reference line, with ~10% of the experimental data points sitting outside the 95% confidence bands. Nevertheless the levels of breakdown voltage predicted by the CPF that will result in a 10%, 50% and 95% probability of breakdown can be extracted; with these values shown to be 121kV, 129kV and 140kV respectively.

The associated time to breakdown of the mineral oil samples under positive nanosecond impulse stress was also shown by the KS normality test to be distributed normally (p-value 0.66). From the CPF produced from the data, shown in Figure 6-3b, it is clear that the experimental data fits well with the predicted distribution with all but two data points contained within the 95% confidence bands. Values of time to breakdown which correspond to a 10%, 50% and 95% probability of fluid breakdown were predicted by the CPF to be 228ns, 329ns 458ns respectively.



(a) (b)

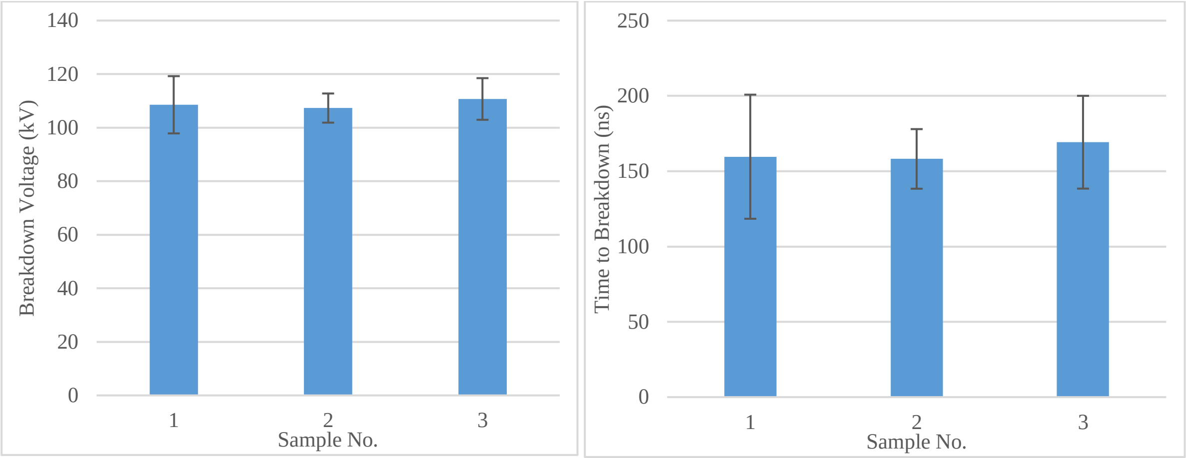
Figure 6-4; *Probability plots for 'As Received' mineral oil; CPFs for negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

It is clear from the CPF shown in Figure 6-4a that breakdown voltage data obtained during the stressing of the ‘As Received’ mineral oil samples with negative nanosecond impulse is not distributed normally with breakdown occurring at either 156kV (37% of all breakdowns) or 157kV (63% of all breakdowns). This non-conformance of the data to a normal distribution was also confirmed by the KS normality test (p-value <0.01). It is therefore impossible to extract the values of voltage from the CPF which would result in breakdown of the ‘As Received’ mineral oil under negative nanosecond impulse.

Unlike the breakdown voltage data, the time to breakdown data measured when the ‘As Received’ samples of mineral oil were exposed to nanosecond impulses of negative polarity was shown by the KS normality test to be distributed normally (p-value 0.19). As can be seen from the CPF (Figure 6-4b) 90% of the experimental data points reside within the confidence bands with 60% of the data on, or close, to the distribution reference line. It is therefore possible to take the values of time to breakdown predicted by the CPF which are associated with a 10%, 50% and 95% probability of breakdown of the ‘As Received’ condition mineral oil; 709ns, 940ns and 1238ns respectively.

6.2.1.2. Breakdown of synthetic ester in the ‘As Received’ condition

When the synthetic ester in the ‘As Received’ condition was stressed with nanosecond impulse voltage the breakdown voltage and associated time to breakdown was consistent over the ten breakdowns of each liquid sample. That is to say that under both positive and negative voltage the liquid samples show no clear upward or downward trend in either of the breakdown parameters. Based on this absence of any visible trend in breakdown voltage, or time to breakdown, it is reasonable to pool these datasets to allow for a much greater sample size for the purpose of mean value analysis (sample size n = 10).



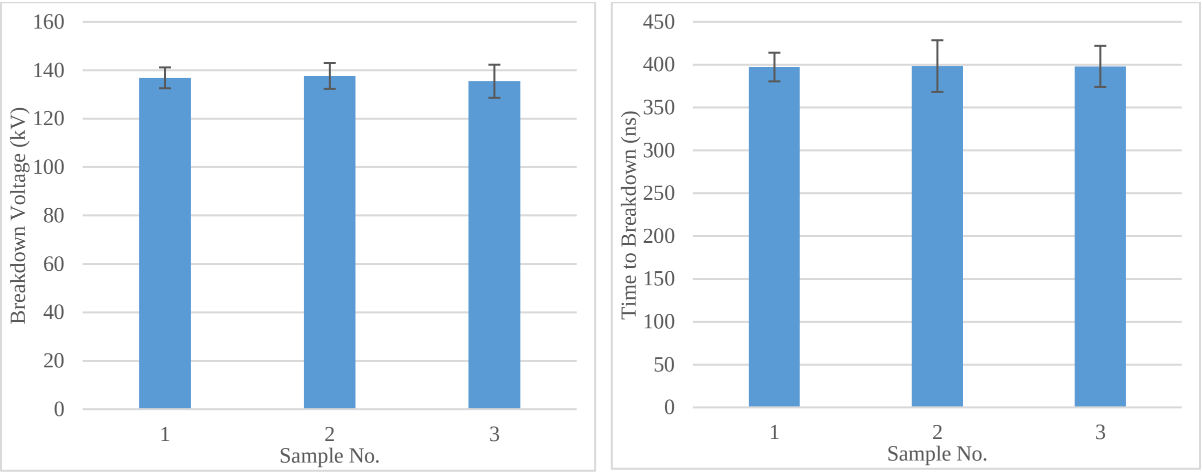
(a)

(b)

Figure 6-5; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the ‘As Received’ synthetic ester samples when the fluid was placed under positive nanosecond impulse stress can be seen above (Figure 6-5a). From the data presented, it is clear that the confidence intervals overlap for all three samples and thus it can be assumed that any differences between samples may not be of statistical significance at the selected degree of confidence. Given the probable lack of statistical difference between the synthetic ester samples, shown with the overlapping of the 95% confidence error bars, it is reasonable to group the three sets of data into one larger dataset (n = 30) for the purpose of cumulative probability analysis.

The average time to breakdown associated with the breakdown of the synthetic ester samples under positive nanosecond impulse (Figure 6-5b) again show a likely lack of statistical difference between samples. Each sample is seen to require a similar time to breakdown, with only a 7% difference in the highest and lowest average values; calculated for Sample 3 (169ns) and Sample 2 (158ns) respectively. This difference is slightly higher than that which exists between the breakdown voltages of the samples (7% as compared with 4% for voltage). Despite this larger difference, it is also possible due to the overlapping confidence intervals to group the time to breakdown data into a single dataset for CPF analysis.



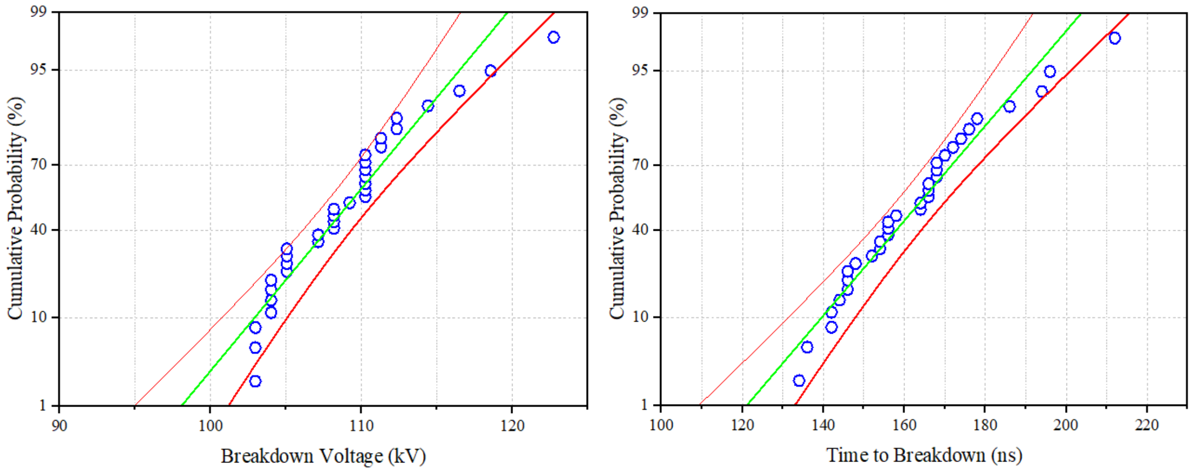
(a)

(b)

Figure 6-6; *Negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Figure 6-6a shows the average values of breakdown voltage calculated for the ‘As Received’ synthetic ester samples when the fluid was stressed with negative nanosecond impulse. It is clear from the figure that each sample requires an almost identical level of voltage to cause breakdown, with only a 1% difference between the highest and lowest average values. However, given that the confidence intervals overlap in all cases any difference between sample averages may not represent statistically significance.

The average time to breakdown calculated for each of the three synthetic ester samples placed under negative nanosecond impulse stress have been shown in Figure 6-6b. As with the breakdown voltage data (Figure 6-6a) it can be assumed that a statistical difference in the average values of time to breakdown calculated for each of the liquid samples may not be present given the overlapping of the confidence intervals. Given that the average values of time to breakdown calculated for each sample are so close together (<1% difference between averages), and that they are almost equal to the nominal rise-time of the impulse (400ns), the discrepancy between breakdown voltage and time to breakdown can be attributed to small changes in the experimental waveform from test-to-test.



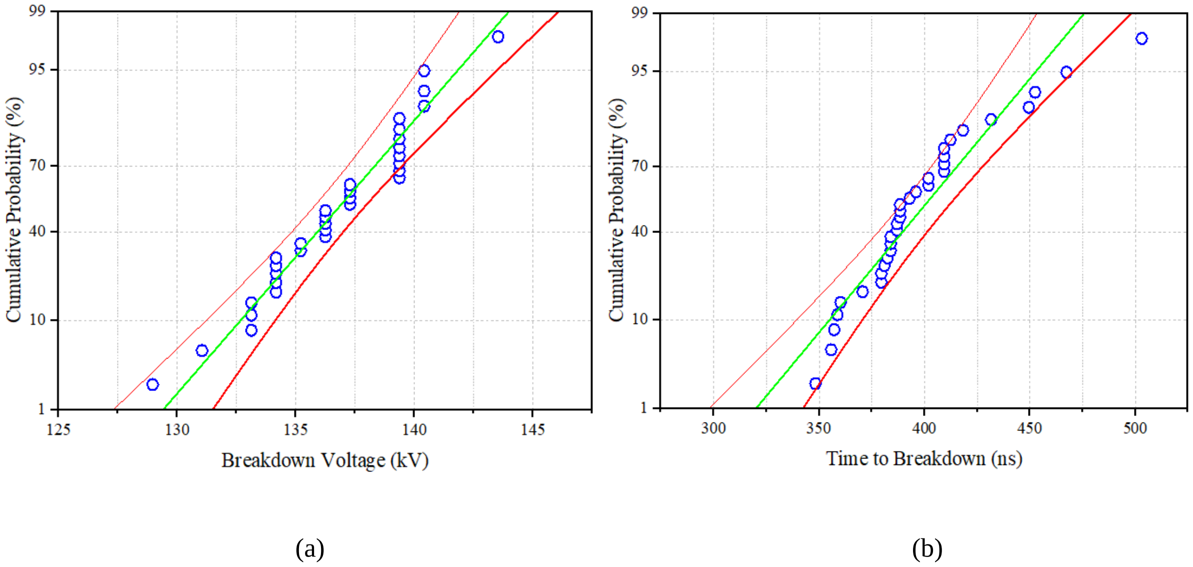
(a) (b)

Figure 6-7; *Probability plots for 'As Received' synthetic ester; CPFs for positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained from experiments involving the stressing of the ‘As Received’ synthetic ester samples with positive nanosecond impulse was shown by the KS normality test to be normally distributed (p-value 0.5). It is clear from the CPF (Figure 6-7a) that multiple breakdowns of the fluid occur at four specific levels of voltage; 104kV, 105kV and 108kV (each accounting of 13% of all breakdowns) as well as 110kV (27% of all breakdowns). Despite this, the experimental data fits reasonably well with the distribution reference line, with all but two data points contained within the 95% confidence bands. From the CPF shown in Figure 6-7a it is possible to extract the levels of voltage predicted to result in a 10% to 95% probability of fluid breakdown; 103kV ($V_{10\%}$), 109kV ($V_{50\%}$) and 117kV ($V_{95\%}$).

The CPF produced from the experimental time to breakdown data can be seen above (Figure 6-7b). The data was confirmed by the KS normality test to follow a normal distribution, returning a goodness of fit coefficient of 0.93. Given that the data has such a high p-value it is not surprising that it conforms well with the predicted distribution, with 87% of all data residing on the reference line and 93%

contained within the confidence banding. From the CPF the values of time to breakdown predicted to cause a 10%, 50% and 95% probability of breakdown of the synthetic ester under positive nanosecond impulse are shown to be 140ns, 162ns and 192ns respectively.



(a)

(b)

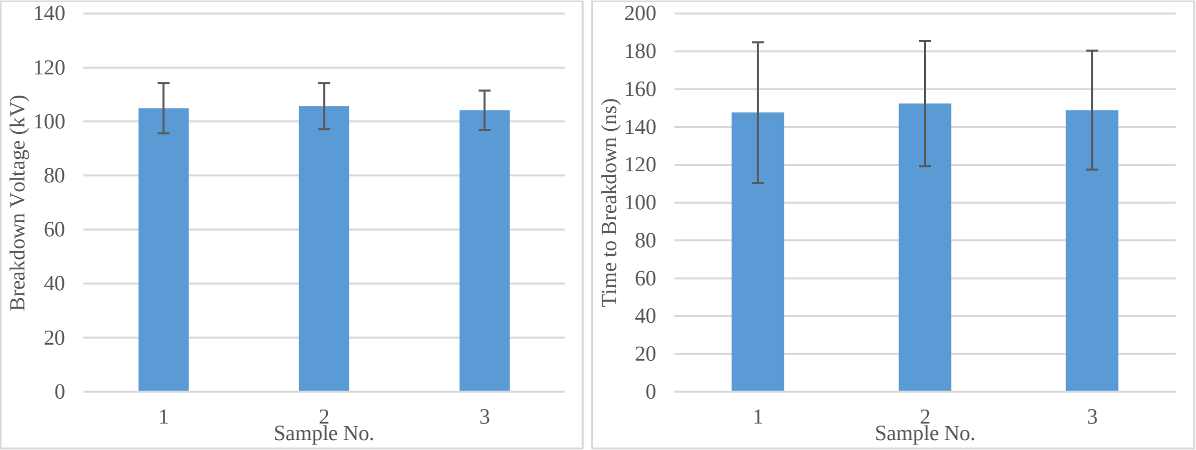
Figure 6-8; *Probability plots for 'As Received' synthetic ester; CPFs for negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The normal distribution of the experimental breakdown voltage data obtained during the testing of the synthetic ester samples under negative nanosecond impulse stress was confirmed by the KS normality test (p-value 0.28). As with the data obtained under positive voltage stress there again exists specific levels of voltage at which multiple breakdowns occur; shown by vertical lines of experimental data points within the distribution. These are seen to occur at 133kV (10% of data), 134kV (17% of data), 136kV (17% of data), 137kV (13% of data) 139kV (27% of data) and 140kV (10% of data). This can be attributed to breakdown of the synthetic ester under negative energisation taking place near the peak of the applied impulse where the change in voltage is minimal. Despite this, the levels of breakdown voltage corresponding to a 10%, 50% and 95% probability of breakdown can still be extracted from the CPF, with these predicted to be 133kV, 137kV and 142kV respectively.

The time to breakdown data measured during the stressing of the synthetic ester with negative nanosecond impulse was shown to be of normal distribution, with the data generating a p-value of 0.36. Unlike the breakdown voltage data (Figure 6-8a), the time to breakdown data (Figure 6-8b) is seen to be distributed reasonably evenly along the reference line. That said there is multiple breakdowns at 409ns, which accounts for 13% of the experimental data points. Again, this is attributed to breakdown of the synthetic ester under negative nanosecond impulse taking place on, or close to, the peak of the voltage impulse. Nevertheless, the predicted values of time to breakdown at the percentiles of interest can still be taken; with these shown to be 355ns ($t_{10\%}$), 398ns ($t_{50\%}$) and 453ns ($t_{95\%}$).

6.2.1.3. Breakdown of natural ester in the 'As Received' condition

When the breakdown voltage and time to breakdown data obtained from tests involving the 'As Received' natural ester (relative humidity ~ 9%) under nanosecond impulse was examined, no upward or downward trend was observed for any of the three liquid samples for either impulse polarity. The lack of any clear trend in the data allowed for the grouping of the ten separate breakdowns experienced by each sample into six discrete datasets, three per impulse polarity, for mean value analysis.

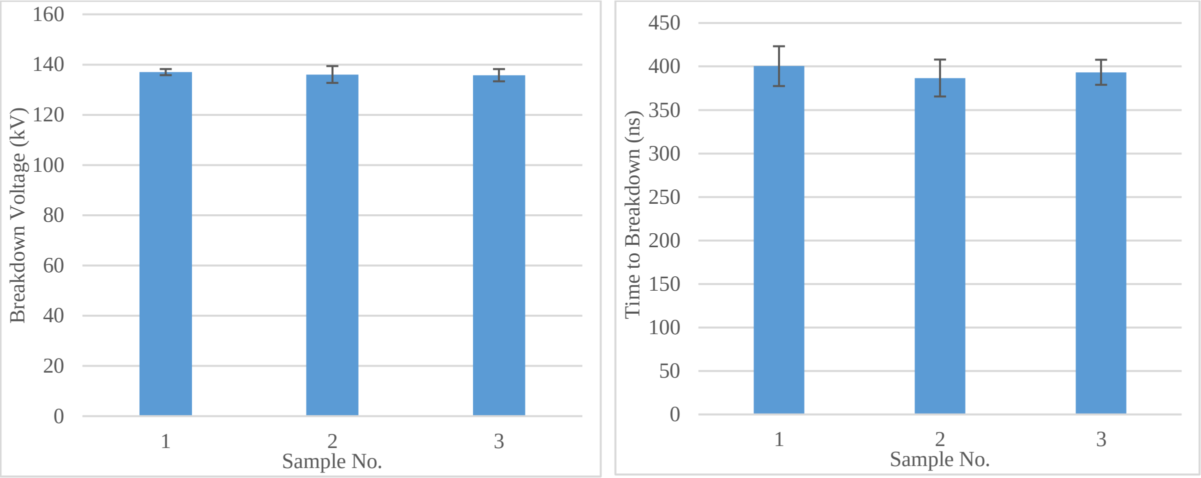


(a) (b)

Figure 6-9; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages calculated for each of the three 'As Received' natural ester samples when stressed with positive polarity nanosecond impulse are presented above (Figure 6-9a). It is evident that again all sample confidence intervals overlap and therefore statistical similarity may exist in level of voltage required to cause breakdown of all three fluid samples. This also allows for the grouping of the experimental data into one large dataset for the purpose of CPF analysis.

The average time to breakdown of each of the 'As Received' natural ester samples may be not statistically different from one another given the degree of overlap in the 95% confidence intervals. From Figure 6-9b it is clear that slightly different behaviour is seen in time to breakdown than was observed in breakdown voltage; with Sample 2 requiring the longest time to breakdown (152ns), as expected, but with Sample 1 (148ns), as opposed to Sample 3 (150ns), the shortest. Given that the difference in breakdown parameters between Sample 1 and Sample 3 is only 1%, this disagreement between breakdown voltage and time to breakdown can be attributed to slight variations in the applied impulse from test-to-test that arise from parasitic elements present within the experimental system.

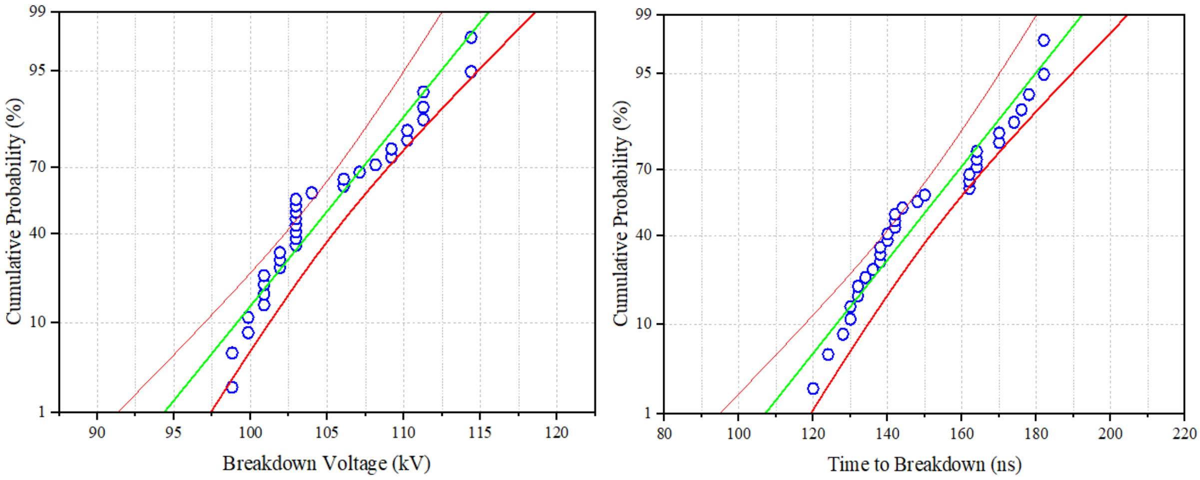


(a) (b)

Figure 6-10; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'As Received' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average values of breakdown voltage calculated for each of the three 'As Received' natural ester samples obtained when the fluid was stressed with negative nanosecond impulse can be seen in Figure 6-10a. Again the confidence intervals of all three liquid samples overlap and thus it can be assumed that statistical difference in the breakdown voltage of the samples may be absent at the selected degree of confidence. Given the closeness of the calculated averages, as well as the overlapping error bars, it is allowable that the three separate sample datasets are grouped for the purpose of CPF analysis.

Figure 6-10b shows the average values of time to breakdown calculated for each of the natural ester samples when exposed to nanosecond impulses of negative polarity. As with breakdown voltage there is a numerical, unlikely to be statistical, difference between the highest and lowest average values of time to breakdown; with this difference larger than that which exists in the breakdown voltage data (3% as compared with ~1%). The reason for this larger difference in sample-to-sample averages of the time to breakdown parameter is as a result of the specific point on the voltage waveform at which breakdown occurs. As breakdown takes place on the peak, or plateau, of the applied impulse the change in voltage is at a minimum over a long timescale.



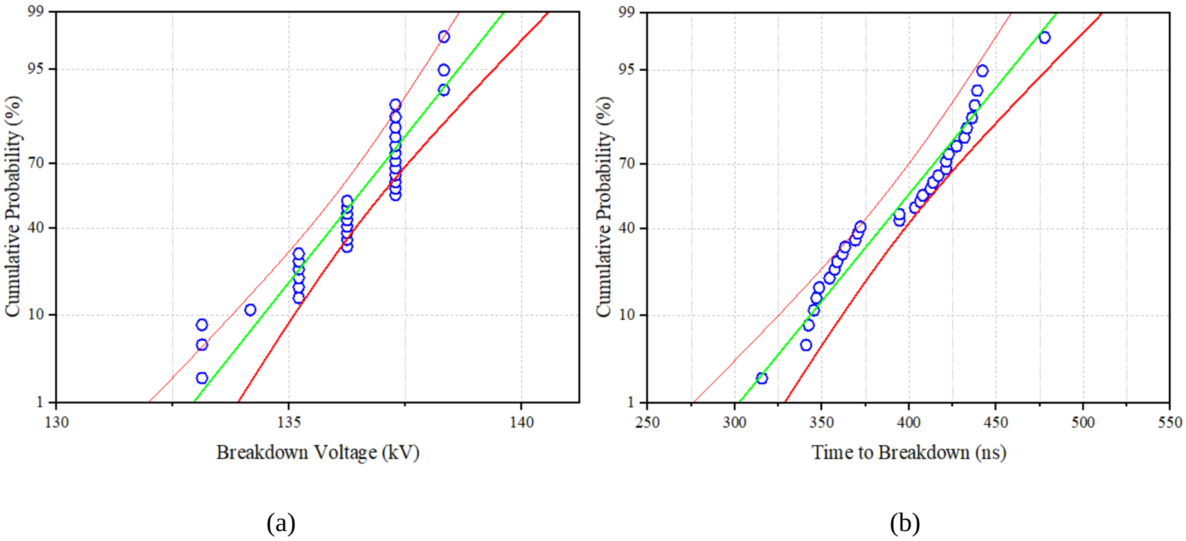
(a)

(b)

Figure 6-11; *Probability plots for 'As Received' natural ester; CPFs for positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF shown in Figure 6-11a clearly demonstrates that breakdown voltage data obtained from tests when the ‘As Received’ natural ester samples were stressed with positive nanosecond impulse is not distributed normally. Breakdown of the fluid is seen to occur multiple times at 103kV (27% of all breakdowns) as well as at 101kV (13% of breakdowns) and 102kV (10% of breakdowns). This non-conformance of the data to a normal distribution was also shown by the KS normality test (p-value 0.03). It is therefore impossible to extract the values of breakdown voltage from the CPF that would result in breakdown of the ‘As Received’ natural ester samples when stressed with positive nanosecond impulse.

Unlike the breakdown voltage data, the time to breakdown data measured when the ‘As Received’ samples of natural ester were stressed with nanosecond impulses of positive polarity is distributed normally (p-value 0.23). All but two experimental data points reside within the confidence bands with 90% of the data on, or close, to the distribution reference line. It is therefore possible to take the values of time to breakdown predicted by the CPF which are associated with a 10%, 50% and 95% probability of breakdown of the natural ester samples in the ‘As Received’ condition; 126ns, 150ns and 180ns respectively.



(a)

(b)

Figure 6-12; *Probability plots for 'As Received' natural ester; CPFs for negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

From the CPF generated with the breakdown voltage data obtained when the ‘As Received’ natural ester samples were stressed with negative nanosecond impulse it is clear that breakdown of the fluid predominately occurred at three voltage levels; 135kV, 136kV and 137kV which account for 20%, 27% and 40% of breakdowns respectively. Despite the profile of the CPF, the data was confirmed by the KS normality test to be distributed normally, though the data did produce a low p-value (0.09). Nevertheless, as the data is normally distributed it is possible to obtain the levels of voltage predicted to cause a 10%, 50% and 95% likelihood of fluid breakdown; 134kV, 136kV and 139kV respectively.

The time to breakdown data associated with the breakdown of the natural ester under negative nanosecond impulse was also shown by the KS normality test to follow a normal distribution (p-value 0.59). Given that this coefficient is much higher than that associated with the breakdown voltage data (0.59 as compared with 0.09) it is not surprising that the time to breakdown CPF adopts a much more typical profile, with all data points seen to be evenly distributed along the reference line and contained within the confidence bands. From the CPF the times to breakdown that are predicted to result in a 10%, 50% and 95% probability of breakdown were shown to be 343ns, 393ns and 458ns respectively.

6.2.1.4. Summary of breakdown of dielectric fluids in 'As Received' condition

The preceding sections of this chapter described the results of experiments in which samples of the three dielectric liquids in the 'As Received' condition (Relative humidity 9% to 21%) were stressed with 0.4μs rise-time impulses of both positive and negative polarity. Analysis of the experimental data obtained for each of the liquid samples showed no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, as the number of breakdowns increased, irrespective of energisation polarity. This allowed for the pooling of sample data into three discrete datasets for each of the three liquids for a given impulse polarity to used in mean value analysis. Review of this data demonstrated that statistical difference may not exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the three discrete datasets into a larger pool for the means of cumulative probability analysis. Calculated values of the chosen breakdown parameters derived from both the mean and CPF analysis have been summarised in Table 6-1.

Table 6-1; *Average breakdown voltage and time to breakdown of 'As Received' dielectric fluids when stressed with 0.4μs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	129 ± 11.4kV	121kV	140kV	0.12
	MIDEL 7131	109 ± 7.9kV	103kV	117kV	0.5
	Envirotemp FR3	105 ± 7.7kV	N/A	N/A	0.03
Negative impulse	Shell Diala S4	157 ± 0.9kV	N/A	N/A	<0.01
	MIDEL 7131	137 ± 5.3kV	133kV	142kV	0.28
	Envirotemp FR3	136 ± 2.4kV	134kV	139kV	0.09
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	329 ± 134ns	227ns	458ns	0.66
	MIDEL 7131	162 ± 30ns	140ns	192ns	0.93
	Envirotemp FR3	150 ± 31ns	126ns	180ns	0.23
Negative impulse	Shell Diala S4	941 ± 307ns	709ns	1238ns	0.19
	MIDEL 7131	398 ± 57ns	355ns	453ns	0.36
	Envirotemp FR3	394 ± 67ns	343ns	458ns	0.59

Table 6-1 shows the average breakdown voltage and time to breakdown of the three dielectric fluids in the ‘As Received’ condition under positive and negative nanosecond impulse stress. The stated values, V_{mean} and t_{mean}, relate to the average values of a given parameter ± the 95% confidence interval as calculated from the entire dataset ($n = 30$) for a given liquid and impulse polarity. $V_{10\%}$ to $V_{95\%}$ represent the probability values of the breakdown parameters for a given liquid as predicted by the CPF, with the p-values obtained from the KS normality test for each dataset also given. Evaluation of the data provided in Table 6-1 shows that when the nanosecond impulse is of positive polarity the mineral oil requires a statistically higher level of voltage to facilitate liquid breakdown than both the synthetic and natural ester fluids; which are likely to possess statistically similar breakdown strengths. This is also the case when the negative nanosecond impulse was applied to the fluids, with the mineral oil having statistically higher breakdown strength than both ester fluids. This is to be expected given that under negative energisation the breakdown of the mineral oil was only possible when the nominal peak amplitude of the voltage impulse was increased from 150kV to 175kV. As was the case when the liquids were placed under positive impulse stress, both ester fluids exhibited a statistically similar breakdown performance; with only a 1% difference in breakdown voltage.

When the fluids were stressed with positive polarity nanosecond impulse identical behaviour is observed in the time to breakdown data as was reported for the breakdown voltage, with the mineral oil requiring a statistically longer time to breakdown; more than twice that of both ester fluids. Again, the ester fluids exhibit similar performance, with both dielectric liquids shown to likely possess a statistically similar time to breakdown when the impulse is of positive polarity. When the impulse was of negative polarity, the mineral oil again shows the best breakdown performance, once more requiring a statistically longer time to breakdown than both the synthetic and natural ester fluids. Under such conditions, the time to breakdown of the mineral oil is seen to be ~2.4 time longer than both ester fluids despite the voltage being of a higher peak amplitude (175kV compared with 150kV). This clearly demonstrates that irrespective of impulse polarity the mineral oil offers significantly better dielectric performance than both synthetic and natural ester fluids when under nanosecond impulsive voltage stress.

Under positive nanosecond impulse, the CPF predicts that the mineral oil requires a higher level of breakdown voltage at all percentiles of interest; between 17% to 20% greater than the synthetic ester. Prediction of the breakdown of natural ester under positive nanosecond impulse from the CPF was not possible given that the experimental data did not conform to a normal distribution due to the data failing the KS normality tests (p-value <0.05). The breakdown of the mineral oil is predicted to occur over a wider range of values than the synthetic ester fluid; demonstrating that while mineral oil offers better dielectric strength the breakdown of the synthetic ester is more consistent. When the impulse is of negative polarity, it is now not possible to predict the levels of voltage that will result in the breakdown of the mineral oil, due to the failure of the data to conform to a normal distribution. Breakdown of the synthetic ester is higher than the natural ester at all but the lowest ($V_{10\%}$) percentiles of interest, however only by 2% with both fluids predicted to have very similar breakdown performance under negative polarity nanosecond impulse.

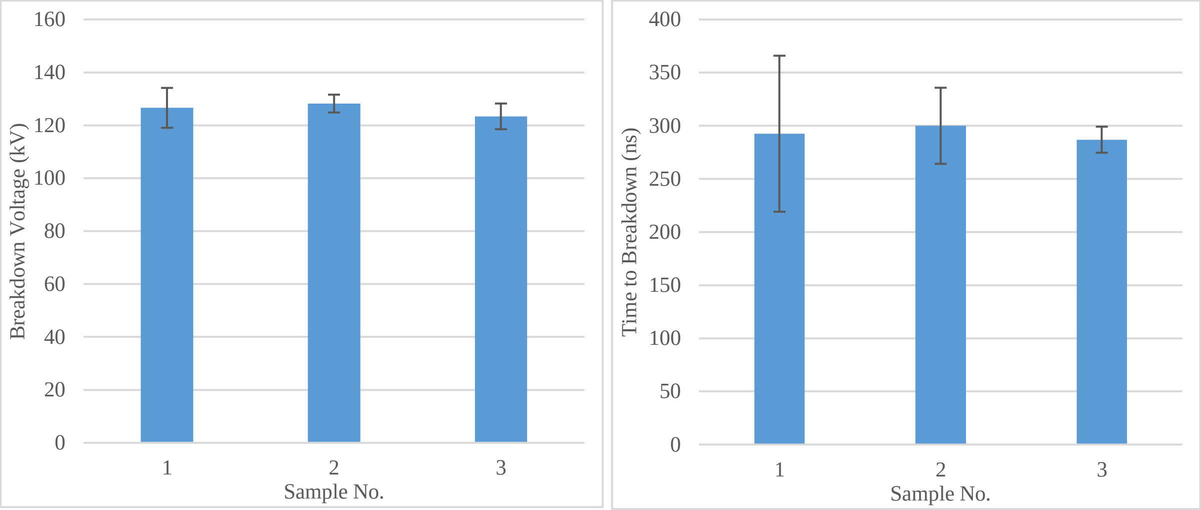
The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow an identical trend to that predicted for the breakdown voltage. The mineral oil is predicted to require the longest time to breakdown of all three dielectric liquids at all percentiles of interests, as much as 2.4 times that of the synthetic ester and ~2.6 times greater than the natural ester. It is now possible to compare the predicted performance of all three liquids with the time to breakdown data of the natural ester now following a normal distribution (unlike the breakdown voltage of the fluid). Predicted values of time to breakdown are similar for both ester fluids. That said the synthetic ester is predicted to require as much as 11% longer to breakdown than the natural ester under positive polarity voltage. The spread of predicted values is largest in the data associated with the breakdown of the mineral oil, with the breakdown of the synthetic ester predicted to occur over the narrowest range. Similar to what is seen with the natural ester under positive energisation, the data associated with the time to breakdown of the mineral oil under negative voltage stress is now seen to be distributed normally; facilitating the comparison of the time to breakdown of all three liquids. The longest values of time to breakdown when under negative voltage stress are predicted for the mineral oil and the natural ester the shortest, except at the highest percentile of interest where the synthetic ester is predicted to have the shortest time to breakdown. The range of predicted times at which the breakdown of the mineral oil will occur again span the widest range, with those associated with the synthetic ester the narrowest. This is identical to the predictions made with the experimental data obtained under positive impulse stress.

6.2.2. Breakdown of liquids in the ‘Ambient humidity’ condition

The sections that follow present and discuss the results pertaining to the bulk breakdown performance of the chosen dielectric fluids in the ‘Ambient humidity’ condition. Fluids in this state possess relative humidity of ~35%. As described in Section 3.3.1, the desired level of relative humidity was achieved by allowing the fluids, which were in open containers, to sit within the laboratory environment until the relative humidity of the fluid reached equilibrium with ambient levels.

6.2.2.1. Breakdown of mineral oil in the ‘Ambient humidity’ condition

The values of breakdown voltage and time to breakdown measured for the ten breakdowns of each of the ‘Ambient humidity’ mineral oil samples have shown that no clear trend, either upward or downward, exists across the ten breakdowns of each sample. This absence of discernible tendency within the data has allowed for the grouping of sample data into discrete datasets, three for a given impulse polarity, each consisting of ten breakdowns to be used for mean value analysis.

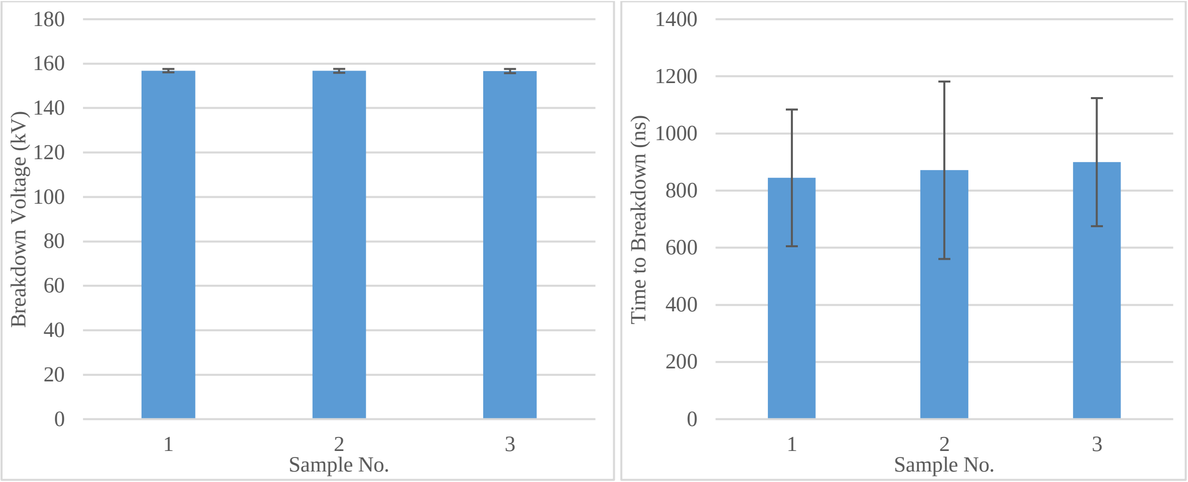


(a) (b)

Figure 6-13; *Positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the three ‘Ambient humidity’ mineral oil samples when under positive nanosecond impulse stress are shown in Figure 6-13a. As can be seen the confidence intervals of each sample overlap, thus implying that it is likely that the level of voltage required to cause breakdown is statistically similar. Given this likelihood of the absence of statistical difference in the data associated with each sample it can be pooled together to form a single dataset (n = 30) to be used during cumulative probability analysis.

Figure 6-13b shows the average time to breakdown calculated from data obtained during experiments which involved stressing the ‘Ambient humidity’ mineral oil with positive polarity nanosecond impulses. As with breakdown voltage, all three samples are likely to have an absence of statistical difference between average values of time to breakdown. The time to breakdown data is in good agreement with that relating to the breakdown voltage of the ‘Ambient humidity’ mineral oil under nanosecond impulses of positive polarity.

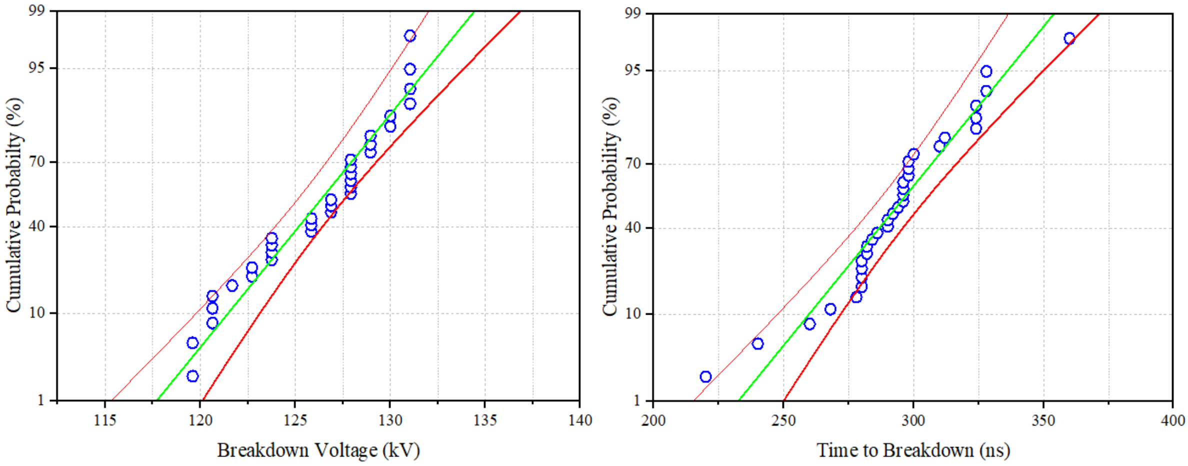


(a) (b)

Figure 6-14; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the three ‘Ambient humidity’ mineral oil samples when the fluid was exposed to negative nanosecond impulse is shown in Figure 6-14a. As previously explained (Section 6.2 and 6.2.1.1), the nominal output voltage of the impulse circuit had to be increased from 150kV to 175kV to achieve breakdown of the mineral oil when the nanosecond impulse was of negative polarity. Despite this, breakdown of the mineral oil under negative nanosecond impulse still regularly occurred on the plateau of the voltage impulse. Consequently, no difference exists between the average values of breakdown voltage, with each sample returning a value of 157kV. It is therefore not surprising that statistical difference is unlikely to be present between the breakdown voltages of each sample.

The average time to breakdown of each ‘Ambient humidity’ sample of mineral oil when stressed with nanosecond impulses of negative polarity is shown above (Figure 6-14b). Even though there was no difference in the average breakdown voltage of each sample (Figure 6-14a), there is a 6% variation between the longest and shortest values of time to breakdown. This can be attributed to breakdown of the fluid taking place on the plateau of the energising impulse where a minimal change in voltage will occur over a long timescale. It is clearly evident that breakdown occurs at such a point on the impulse as the average values of time to breakdown calculated for each mineral oil sample are more than twice the nominal rise-time of the impulse (400ns).



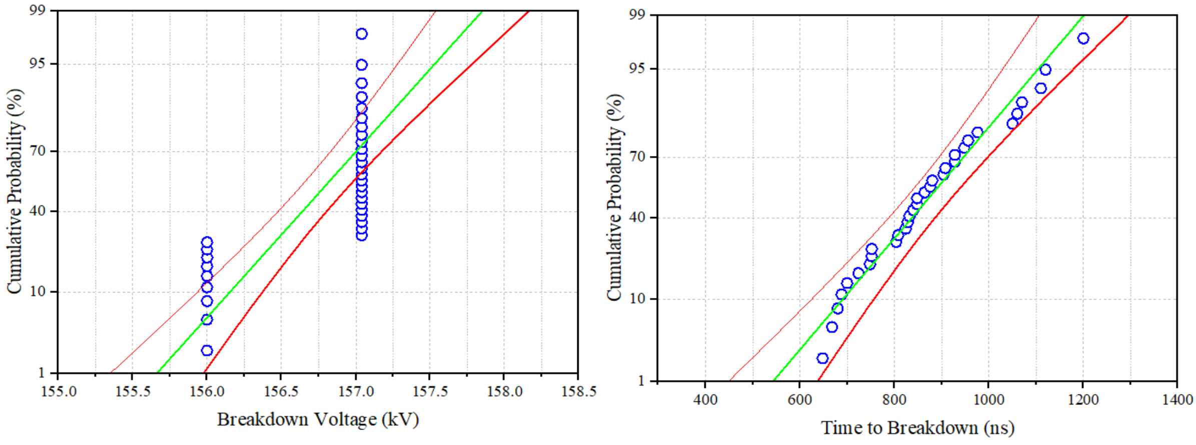
(a) (b)

Figure 6-15; *Probability plots for 'Ambient humidity' mineral oil; CPFs for positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The data pertaining to the breakdown of the 'Ambient humidity' mineral oil when stressed with positive polarity nanosecond impulse was shown by the KS normality test to be distributed normally, returning a goodness of fit coefficient (p-value) of 0.32. That said it is clear from the CPF produced from the data (Figure 6-15a) that multiple breakdowns occurs at particular levels of voltage ranging between 121kV and 132kV. The largest number of these multiple breakdowns occurs as 127kV, which accounts for 20% of all recorded breakdown events of the 'Ambient humidity' mineral oil under positive nanosecond impulse. Irrespective of this, as the data was confirmed to be normally distributed it is possible to extract the predicted levels of breakdown voltage at all percentiles of interest. These were forecast by the CPF to be 122kV ($V_{10\%}$), 126kV ($V_{50\%}$) and 132kV ($V_{95\%}$).

The CPF generated from the time to breakdown data obtained when the 'Ambient humidity' samples of mineral oil were exposed to nanosecond impulses of positive polarity is shown above (Figure 6-15b).

This data was subjected to the KS normality test and proved to be normally distributed (p-value 0.34). Given this goodness of fit coefficient, it is not surprising that there is deviation of the experimental data from the distribution reference line. Multiple breakdowns at a given value of time to breakdown only observed to occur once (325ns) which accounts for 10% of the experimental data points. The values of time to breakdown that are predicted by the CPF to cause a 10%, 50% and 95% probability of fluid breakdown are 260ns, 293ns and 336ns respectively.



(a)

(b)

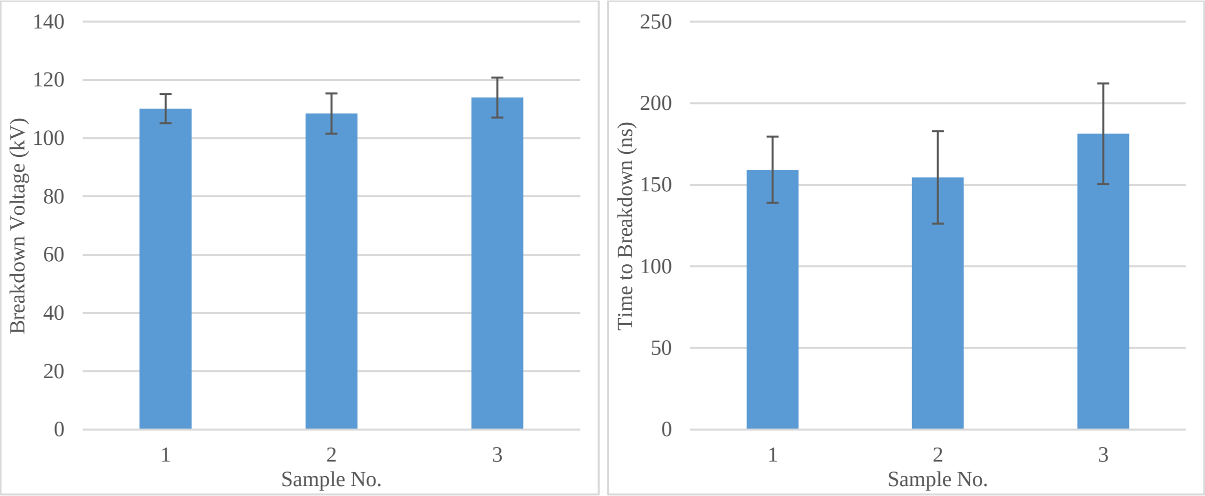
Figure 6-16; *Probability plots for 'Ambient humidity' mineral oil; CPFs for negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF shown in Figure 6-16a clearly demonstrates that breakdown voltage data obtained during the stressing of the ‘Ambient humidity’ mineral oil samples with negative nanosecond impulse is not distributed normally with breakdown occurring at either 156kV (30% of all breakdowns) or 157kV (70% of all breakdowns). This non-conformance of the data to a normal distribution was confirmed through application of the KS normality test (p-value <0.01). Consequently, the values of breakdown voltage that would result in breakdown of the ‘Ambient humidity’ samples of mineral oil under negative nanosecond impulse cannot be extracted from the CPF.

Unlike the breakdown voltage data, the time to breakdown data measured when the ‘Ambient humidity’ samples of mineral oil were exposed to nanosecond impulses of negative polarity was shown by the KS normality test to be distributed normally (p-value ~1). Given that the data returned such a high p-value, it is unsurprising that the data is in excellent agreement with the distribution reference with all experimental data points residing within the confidence bands and all but two data points on, or close, to the distribution reference line. It is therefore possible to take the values of time to breakdown predicted by the CPF which are associated with a 10%, 50% and 95% probability of breakdown of the ‘Ambient humidity’ mineral oil; 691ns, 872ns and 1104ns respectively.

6.2.2.2. Breakdown of synthetic ester in the ‘Ambient humidity’ condition

Liquid samples of the synthetic ester MIDEL 7131 when in the ‘Ambient humidity condition were stressed with nanosecond impulses of both positive and negative polarity in accordance with the testing methodology described in Section 3.6.1. Upon review of the ten individual breakdowns of each liquid sample no degradation, or increase, in breakdown voltage or time to breakdown was identified, irrespective of the impulse polarity. Since no clear upward or downward trend exists across the dataset of each sample it is reasonable that the ten shots may be grouped into a single dataset, one for each liquid sample (three for a given impulse polarity), to facilitate mean value analysis.

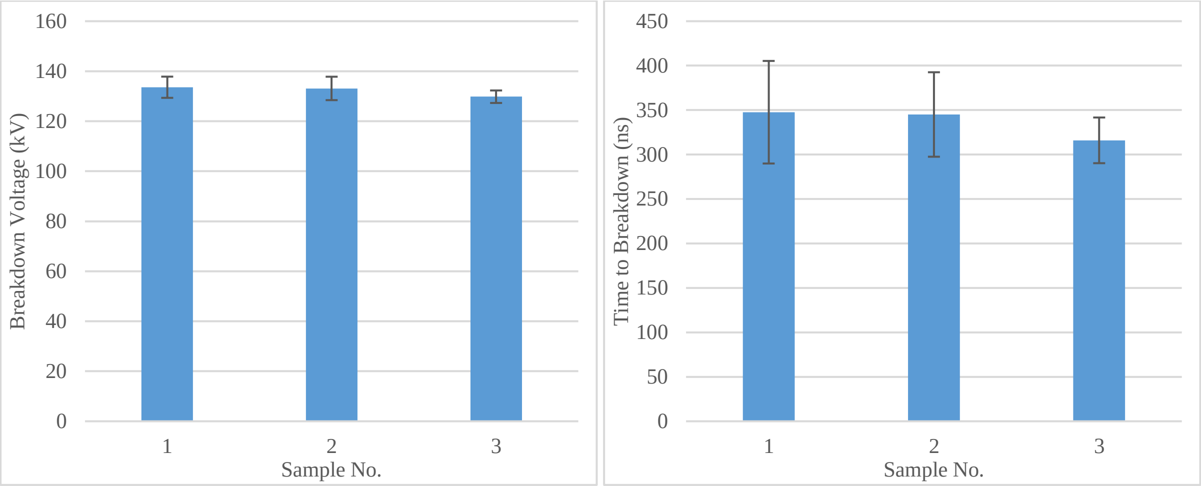


(a) (b)

Figure 6-17; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Figure 6-17a presents the average values of breakdown voltage calculated for the ‘Ambient humidity’ samples of synthetic ester when the fluid was stressed with positive nanosecond impulse voltage. It can once more be said that any differences between the sample means may not be of statistical significance at the selected degree of confidence given that the 95% confidence intervals overlap in all cases. The likely absence of any statistical difference between sample averages means it is reasonable to group the individual data into one single dataset (n = 30) for the purpose of cumulative probability analysis.

The average time to breakdown when each ‘Ambient humidity’ synthetic ester sample was exposed to positive nanosecond impulse is given in Figure 6-17b. Good agreement exists between the values presented in Figure 6-17a (breakdown voltage), with the longest average time to breakdown calculated for Sample 3 (181ns) and the shortest Sample 2 (155ns). This represents a difference of ~14% between samples, almost three times that which exists in the breakdown voltage data (~5%). This discrepancy results from the wider spread of time to breakdown values within the individual sample datasets, with this confirmed by the larger 95% confidence intervals calculated for the data compared to that of the breakdown voltage. Despite this difference, all samples can be assumed to require a statistically similar time to breakdown as all 95% confidence interval overlap.



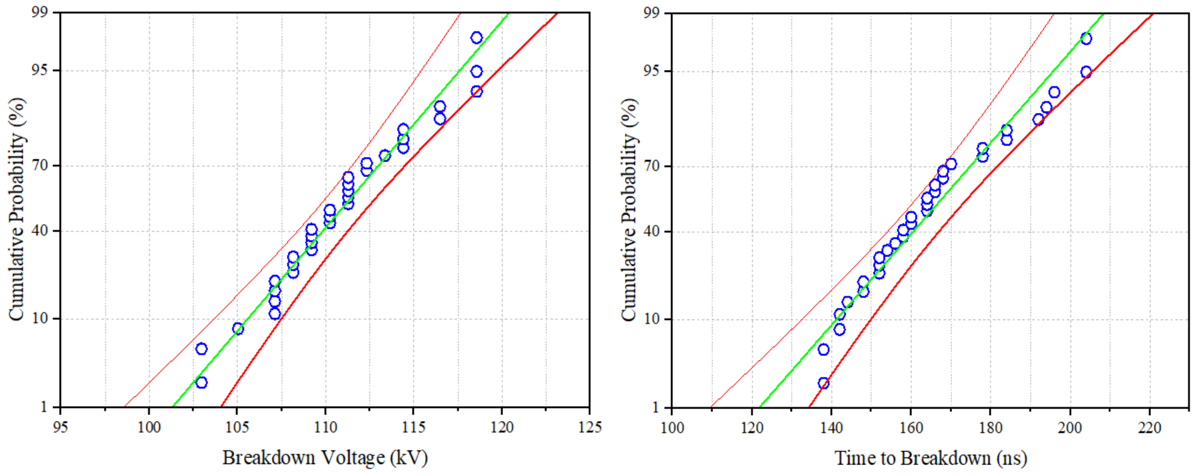
(a)

(b)

Figure 6-18; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Figure 6-18a shows the average breakdown voltage calculated for the three ‘Ambient humidity’ samples of synthetic ester when the liquid was placed under negative nanosecond impulse stress. From the data presented, it is evident that all sample confidence intervals overlap and thus statistically significant difference between calculated averages may not exist.

The average values of time to breakdown associated with the breakdown of the ‘Ambient humidity’ synthetic ester samples stressed with negative polarity nanosecond impulse are shown in Figure 6-18b. It is clear from the figure that identical behaviour exists in the time to breakdown as was observed in the breakdown voltage, with Sample 1 requiring the longest time to breakdown (348ns) and Sample 3 the shortest (316ns). This again represents a larger difference in time to breakdown than exists in breakdown voltage (10% as compared with only 3%). This dissimilarity can be attributed to a number of breakdowns in the Sample 1 dataset occurring near the peak of the impulse. At such a point the change in voltage will be minimal but the variation in time may be large, this will cause outlying data points and increase the size of the confidence intervals; which is evident in the data presented in Figure 6-18b. Consequently all sample confidence intervals overlap and thus statistical similarity may exist in the time to breakdown of all samples; allowing the data to be grouped together (n = 30) for the purpose of CPF analysis.



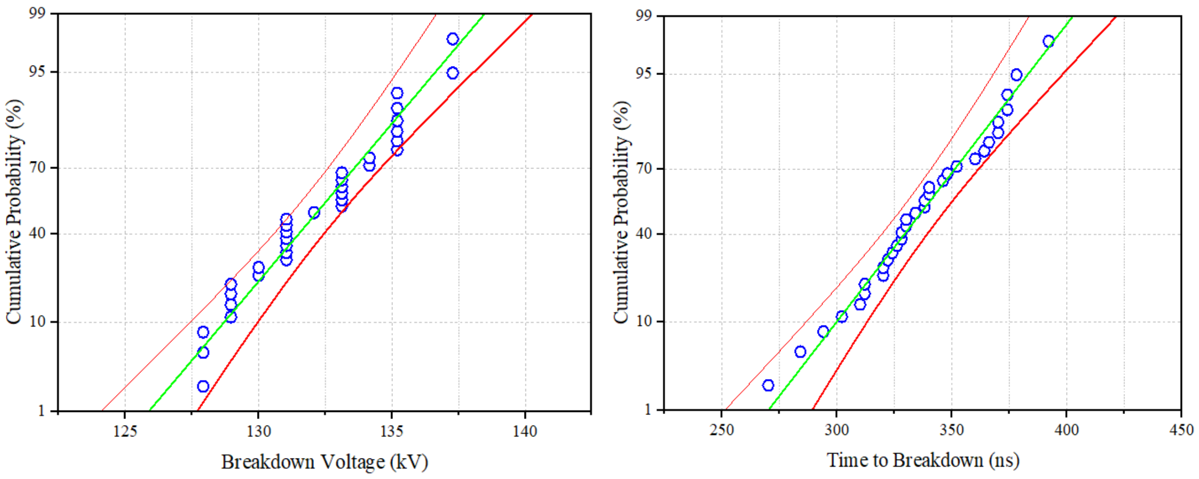
(a)

(b)

Figure 6-19; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF produced from the breakdown voltage data obtained when the ‘Ambient humidity’ synthetic ester samples were stressed with positive nanosecond impulse is shown in Figure 6-19a. Experimental data was confirmed to be of normal distribution with the KS normality test, generating a goodness of fit coefficient (p-value) of 0.67. From the CPF it is clear that breakdown predominately takes place at six discrete levels of voltages, with multiple breakdowns seen to occur between 107kV and 115kV. The most common level of voltage resulting in breakdown of the synthetic ester under positive nanosecond impulse was 111kV, accounting for ~17% of all breakdowns observed. Despite the placement of the experimental data points, it is possible to extract the predicted levels of breakdown voltage at all percentiles of interest; these are shown to be 106kV ($V_{10\%}$), 111kV ($V_{50\%}$) and 118kV ($V_{95\%}$).

Figure 6-19b presents the CPF derived from time to breakdown data measured when stressing the synthetic ester samples with positive nanosecond impulse. The distribution of the data was shown to be normal through use of the KS normality test, with the dataset producing a p-value of 0.57. Given this, it is not surprising that the data is in good agreement with the normal distribution reference line, with all experimental data points contained within the confidence bands and ~87% sitting on, or close, to the reference line. From the CPF it is possible to determine the values of time to breakdown that correspond to a 10%, 50% and 95% probability of fluid breakdown; 142ns, 165ns and 196ns respectively.



(a) (b)

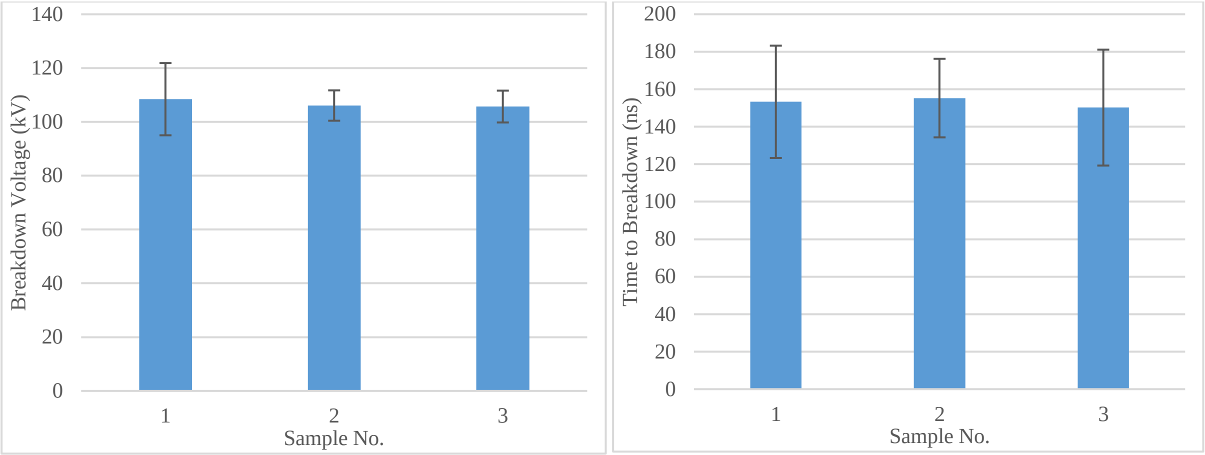
Figure 6-20; *Probability plots for 'Ambient humidity' synthetic ester; CPFs for negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The CPF shown in Figure 6-20a was derived from breakdown voltage data obtained during tests conducted with the ‘Ambient humidity’ synthetic ester when stressed with negative nanosecond impulse. The data conforms to a normal distribution, confirmed with the KS normality test (p-value 0.43). Breakdown of the fluid is seen to occur multiple times at a number of different voltages between 128kV and 135kV, with the most of these multiple breakdowns taking place at 131kV (~23% of all breakdowns). Despite the profile of the CPF and the aforementioned occurrence of multiple breakdowns at certain voltage levels it is possible to extract the values of voltage that would result in breakdown of the fluid at all percentiles of interest. From the CPF 129kV, 132kV and 139kV are predicted to result in a 10%, 50% and 95% probability of breakdown respectively.

Like the breakdown voltage data, the time to breakdown data measured when the ‘Ambient humidity’ samples of synthetic ester were stressed with nanosecond impulses of negative polarity is also distributed normally (p-value ~1). Given that the data returns such a high p-value it follows that good agreement with the distribution reference is present. Clearly from Figure 6-20b it can be seen that this is the case, with all experimental data points residing within the confidence bands as well as being on, or close, to the normal distribution reference line. It is therefore possible to take the values of time to breakdown predicted by the CPF to give a 10%, 50% and 95% probability of breakdown of the synthetic ester samples in the ‘Ambient humidity’ condition; shown to be 300ns, 336ns and 383ns respectively.

6.2.2.3. Breakdown natural ester in the ‘Ambient humidity’ condition

Within the breakdown data obtained for the natural ester Envirotemp FR3 samples in the ‘Ambient humidity’ condition no clear trend can be observed in the breakdown voltage or associated time to breakdown of the liquid samples stressed with either positive or negative nanosecond impulse voltage. The level of breakdown voltage for each individual sample (three for a given impulse polarity) is seen to fluctuate up and down across the data series as is the time to breakdown. The absence of any observable trend in the experimental data again supports the decision to pool individual sample data into a suitably large dataset for the purpose of mean value analysis (n = 10).

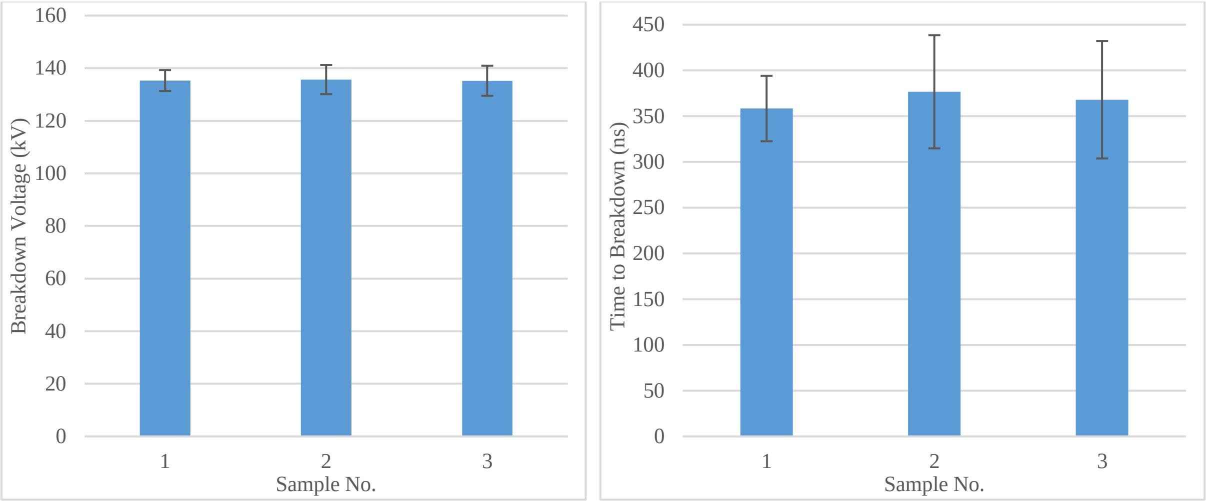


(a) (b)

Figure 6-21; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Evaluation of the data pertaining to the average breakdown voltage of the ‘Ambient humidity’ natural ester samples under positive nanosecond impulse has shown that statistical difference may not exist between the mean values of breakdown voltage calculated for each liquid sample. Again, any variation in average values, due to the overlapping confidence intervals, may not be of statistical significance at the selected degree of confidence and thus the grouping of experimental data into one single dataset for the purpose of CPF analysis is possible.

Review of the average time to breakdown data collected for each liquid sample, provided in Figure 6-21b, again shows that statistical difference may not exist between samples. However, unlike the data on average breakdown voltage (Figure 6-21a), the longest time to breakdown does not occur for Sample 1, rather Sample 2 (155ns), Sample 3 as expected has the shortest average time to breakdown (150ns). Given the closeness of the average values calculated for Sample 1 and Sample 2, 153ns and 155ns respectively, the dissimilarity between breakdown voltage and time to breakdown can be attributed to the wider spread of the values within the Sample 1 dataset that clearly contains outliers that reduce the mean value. This assumption is supported by the large error bars associated with the Sample 1 data (the largest of the three samples).

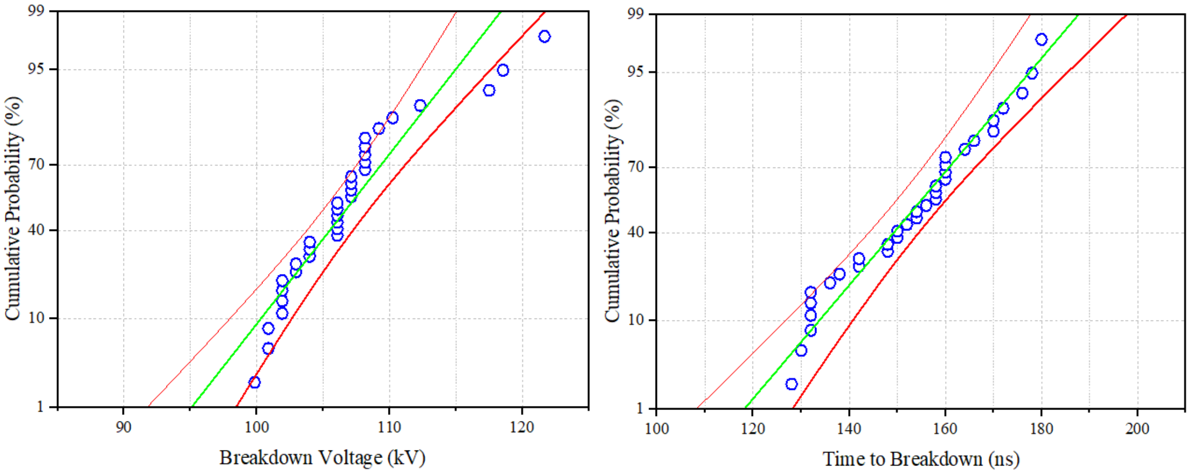


(a) (b)

Figure 6-22; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Ambient humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

Depicted in Figure 6-22a is the average breakdown voltage of the ‘Ambient humidity’ natural ester samples under negative nanosecond impulse stress. From the data presented in Figure 6-22a it is evident that the breakdown of the fluid occurs over a very narrow range of voltages (135kV to 136kV). This 1% difference between the highest and lowest average values of breakdown voltage is unlikely to be of statistical significance given the overlapping of the 95% confidence intervals. It is therefore possible to group the individual data collected for the three liquid samples into one single dataset to facilitate cumulative probability analysis.

The average time to breakdown associated with each sample of the natural ester in the ‘Ambient humidity condition can be seen in Figure 6-22b. It is clear from the figure that the average time to breakdown is in excellent agreement with that of the breakdown voltage; with the highest and lowest average values calculated for Sample 2 (377ns) and Sample 1 (358ns) respectively. However again as the confidence intervals overlap in all cases any numerical dissimilarity in the calculated average values of time to breakdown is unlikely to represent a statistically significant difference.

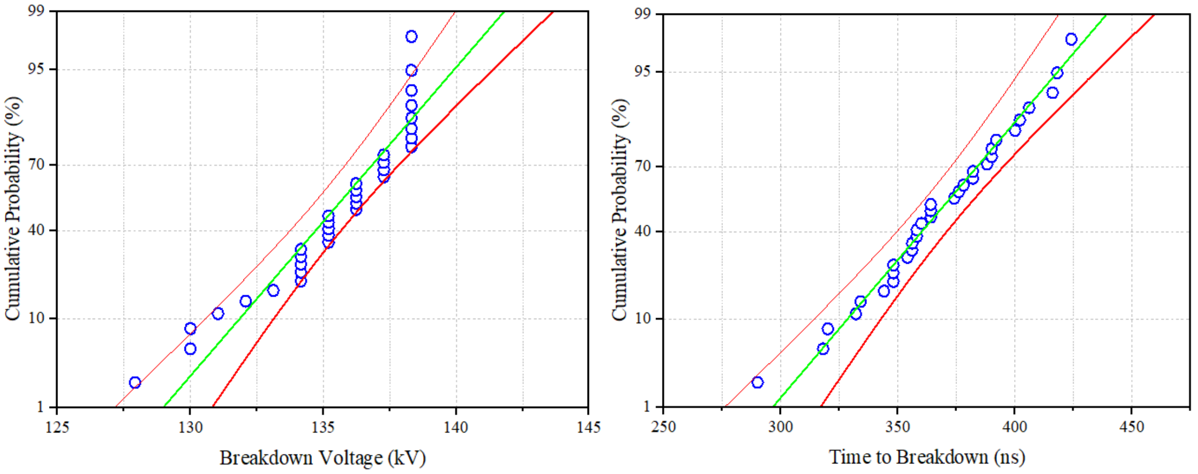


(a) (b)

Figure 6-23; *Probability plots for 'Ambient humidity' natural ester; CPFs for positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The data obtained on the breakdown voltage of the 'Ambient humidity' natural ester when stressed with positive polarity nanosecond impulse was shown by the KS normality test to be distributed normally, returning a goodness of fit coefficient (p-value) of 0.1. From the data, presented in Figure 6-23a, it is clear that multiple breakdowns occur at particular levels of voltage ranging between 102kV to 108kV. The largest number of these multiple breakdowns occur at 106kV, which accounts for 20% of all recorded breakdown events of the 'Ambient humidity' natural ester under positive nanosecond impulse. Irrespective of this as the data was confirmed to be normally distributed it is possible to extract the predicted levels of breakdown voltage at all percentiles of interest. These were forecast by the CPF to be 100kV ($V_{10\%}$), 107kV ($V_{50\%}$) and 115kV ($V_{95\%}$).

The CPF generated from the time to breakdown data obtained when the 'Ambient humidity' samples of natural ester were exposed to nanosecond impulses of positive polarity is shown above (Figure 6-23b). This data was subjected to the KS normality test and proved to be normally distributed (p-value 0.96). Given this high goodness of fit coefficient, it is not surprising that the experimental data agrees well with the distribution reference. Unlike the breakdown voltage data (Figure 6-23a), the time to breakdown data points are evenly distributed along the reference line, however, multiple breakdowns at a given value of time to breakdown are observed, occurring at 132ns, 158ns and 162ns. The values of time to breakdown which are predicted by the CPF to cause a 10%, 50% and 95% probability of fluid breakdown are 134ns, 153ns and 178ns respectively.



(a) (b)

Figure 6-24; *Probability plots for 'Ambient humidity' natural ester; CPFs for negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained when the ‘Ambient humidity’ natural ester samples were exposed to negative polarity nanosecond impulse was confirmed to be distributed normally (p-value 0.45). From the CPF (Figure 6-24a) it is clear that, as with the case when the liquid was placed under positive voltage stress, multiple breakdowns occur at specific levels of voltage. Between 134kV and 138kV multiple breakdowns of the fluid can be seen at 134kV, 135kV and 136kV (each accounting for 17% of all breakdowns) as well as at 137kV and 138kV which account for 13% and 27% of observed breakdowns respectively. Despite this the data is still confirmed by the KS normality test to be of normal distribution and thus is it possible to take the levels of voltage predicted by the CPF to result in a 10% (132kV), 50% (135kV) and 95% (140kV) probability of fluid breakdown.

The data associated with the time to breakdown of the ‘Ambient humidity’ natural ester when the liquid was stressed with negative polarity nanosecond impulse voltage is also of normal distribution. This was confirmed when the data was subjected to the KS normality test with the data returning a near perfect p-value of ~1. Given this, it is not surprising that the data is in excellent agreement with the predicted distribution, with all data contained within the confidence banding and all but one data point residing on the reference line. From the CPF (Figure 6-24b) the values of time to breakdown predicted to result in a 10%, 50% and 95% likelihood of breakdown were taken as 328ns, 368ns and 418ns respectively.

6.2.2.4. Summary of breakdown of dielectric liquids in the ‘Ambient humidity’ condition

The preceding sections described the data obtained when the chosen dielectric liquids in the ‘Ambient humidity’ condition were stressed with nanosecond impulses of both positive and negative polarity. Obtained experimental data was evaluated and it was observed that no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, existed; irrespective of energisation polarity. This allowed for the pooling of sample data into three discrete datasets for each of the three liquids which was then used in mean value analysis. Evaluation of this data demonstrated that statistical difference is unlikely to exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the three discrete datasets into a larger pool for the means of cumulative probability analysis. Breakdown parameters (breakdown voltage and time to breakdown) derived from both the mean value and CPF analysis have been summarised in Table 6-2.

Table 6-2*; Average breakdown voltage and time to breakdown of 'Ambient humidity' dielectric fluids when stressed with 0.4µs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	126 ± 6.1kV	122kV	132kV	0.32
	MIDEL 7131	111 ± 7kV	106kV	118kV	0.67
	Envirotemp FR3	107 ± 8.5kV	100kV	115kV	0.1
Negative impulse	Shell Diala S4	157 ± 0.8kV	N/A	N/A	<0.01
	MIDEL 7131	132 ± 4.6kV	129kV	137kV	0.43
	Envirotemp FR3	135 ± 4.7kV	132kV	140kV	0.45
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-value*
Positive impulse	Shell Diala S4	293 ± 44ns	260ns	336ns	0.34
	MIDEL 7131	165 ± 32ns	142ns	196ns	0.57
	Envirotemp FR3	153 ± 25ns	134ns	178ns	0.96
Negative impulse	Shell Diala S4	872 ± 240ns	691ns	1104ns	~1
	MIDEL 7131	336 ± 48ns	300ns	383ns	~1
	Envirotemp FR3	368 ± 52ns	329ns	418ns	~1

Under positive polarity nanosecond impulse the mineral oil requires a statistically higher level of voltage to facilitate breakdown than both the synthetic and natural ester fluids; which are likely to possess statistically similar breakdown strengths. This is also the case when the negative nanosecond impulse was applied to the fluids, with the mineral oil having statistically higher breakdown strength than both ester fluids. Given that under negative energisation, the breakdown of the mineral oil was only possible when the nominal peak amplitude of the voltage impulse was increased from 150kV to 175kV this is of no great surprise. When placed under negative impulse stress, both ester fluids are again likely to offer a statistically similar breakdown performance; with only a 2% difference in breakdown voltage.

When the fluids were stressed with positive polarity nanosecond impulse identical behaviour is observed in the time to breakdown data as that of the breakdown voltage, with the mineral oil requiring a statistically longer time to breakdown; ~1.8 times and ~1.9 times that of the synthetic ester and natural ester fluids respectively. Again, the ester fluids exhibit similar performance, with both dielectric liquids seen to possess time to breakdown that may be statistically similar at the selected degree of confidence when the impulse is of positive polarity. When the impulse was of negative polarity, the mineral oil again shows the best breakdown performance, once more requiring a statistically longer time to breakdown than both the synthetic ester and natural ester fluids. The time to breakdown of the mineral oil is seen to be ~2.6 times longer than the synthetic ester and ~2.4 times that of the natural ester despite the voltage being of a higher peak amplitude (175kV compared with 150kV). This clearly demonstrates that irrespective of impulse polarity the mineral oil offers significantly better dielectric performance than both synthetic and natural ester fluids when under nanosecond impulsive voltage stress.

Under positive nanosecond impulse, the CPF predicts that the mineral oil requires a higher level of breakdown voltage at all percentiles of interest; as much as 15% and 22% greater than the synthetic ester and natural ester respectively. The breakdown of the mineral oil is predicted to occur over a narrower range of values than both ester fluids; demonstrating that under the testing conditions applied (described in Section 3.6.1) mineral oil offers better dielectric strength as well as a more consistent performance than both ester fluids. When the impulse is negative, it is now not possible to predict the levels of voltage that will result in the breakdown of the mineral oil, due to the failure of the data to conform to a normal distribution. Breakdown of the natural ester is higher than the synthetic ester at all percentiles of interest, however only by 2% with both fluids predicted to have very similar breakdown performance under negative polarity nanosecond impulse.

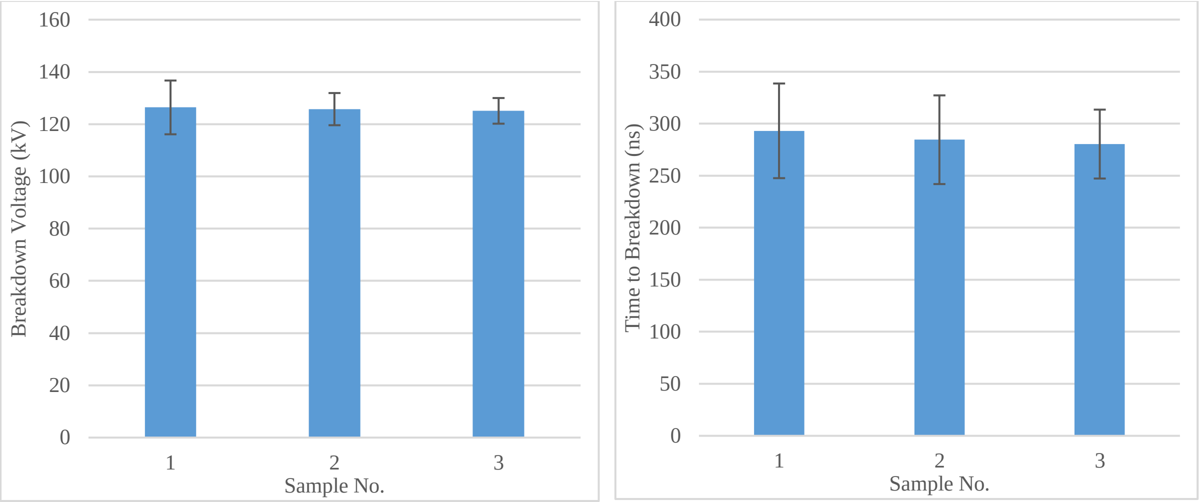
The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow an identical trend to that predicted for the breakdown voltage. The mineral oil predicted to require the longest time to breakdown of all three dielectric liquids at all percentiles of interests, as much as 2.9 times that of the synthetic ester and ~2.6 times greater than the natural ester. Predicted values of time to breakdown are similar for both ester fluids. That said the synthetic ester is predicted to require as much as 10% longer to breakdown than the natural ester under positive polarity voltage. The spread of predicted values is largest in the data associated with the breakdown of the mineral oil, with the breakdown of the natural ester predicted to occur over the narrowest range. The longest values of time to breakdown when under negative voltage stress are predicted for the mineral oil and the synthetic ester the shortest. The range of predicted times at which the breakdown of the mineral oil will occur again span the widest range, with those associated with the synthetic ester the narrowest. The behaviour observed for the ester fluids is in contrast to what was predicted by the CPF when the impulse was of positive polarity; demonstrating that when the impulse is negative the natural ester offers a higher dielectric strength to the synthetic ester but at a cost of lessened predictability in breakdown behaviour.

6.2.3. Breakdown of liquids in the ‘Elevated humidity’ condition

The proceeding sections of this chapter are focused on the presentation and discussion of experimental data obtained from testing of the chosen dielectric liquids in the ‘Elevated humidity’ condition. This signifies liquids with the highest level of relative humidity used within this thesis (>70% relative humidity). To attain this high state of relative humidity the liquids were subjected to a humidification process that increased the moisture content over a short time period; described fully in Section 3.3.1.

6.2.3.1. Breakdown of mineral oil in the ‘Elevated humidity’ condition

When the experimental breakdown voltage and time to breakdown data obtained when the ‘Elevated humidity’ mineral oil (relative humidity 70%) was placed under nanosecond impulse stress was reviewed no noticeable trend could be identified in either parameter under positive or negative voltage stress. That is to say that breakdown voltage, or time to breakdown, did not clearly reduce, or increase, as the number of breakdowns a given sample underwent increased. The lack of trend within this aforementioned data allowed the individual shots to be grouped into six discrete datasets (three for a given polarity of impulse) to be used in mean value analysis.

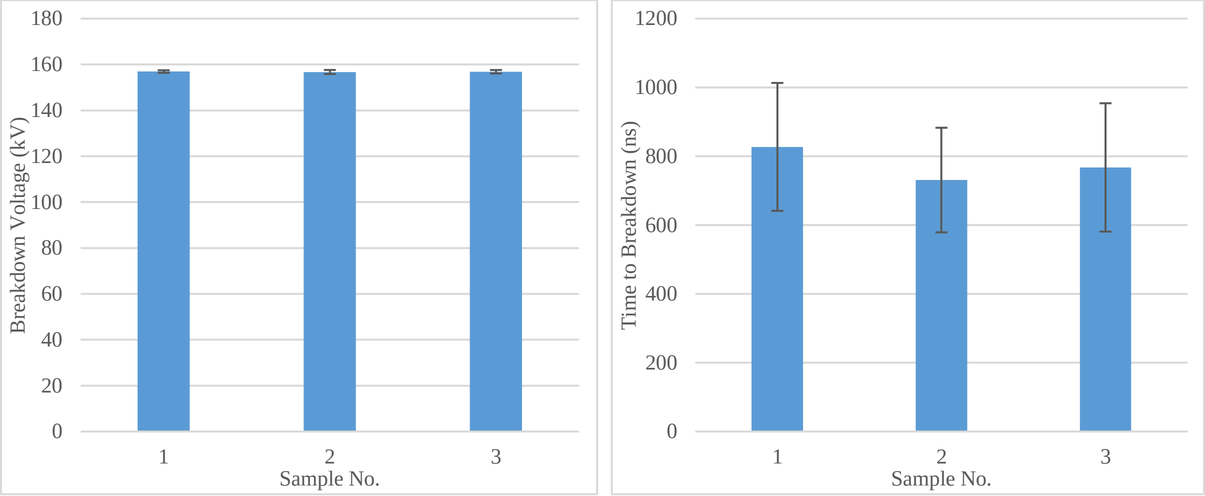


(a) (b)

Figure 6-25; *Positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in ‘Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages of the ‘Elevated humidity’ mineral oil samples obtained under nanosecond impulse voltage of positive polarity are presented above. From Figure 6-25a it can be seen that the average breakdown voltage of each of the samples are very close together with only a 1% difference between the highest and lowest values. Given the closeness of these average values, coupled with the overlapping of the 95% confidence intervals, it is unsurprising that statistical difference may not exist in the sample means. This probable absence of statistical difference in the breakdown voltage of the three samples has allowed for the grouping of the datasets to facilitate accurate cumulative probability evaluation.

Figure 6-25b depicts the average time to breakdown of each mineral oil sample when exposed to the positive nanosecond voltage impulse. As with average breakdown voltage, all sample confidence intervals are seen to overlap and thus it can be assumed that it is likely that all samples require a similar time to breakdown. The average values of time to breakdown show a larger variation than was observed in the breakdown voltage data, 4% as compared with only 1%. This is attributed to the wider spread of the time to breakdown data due to mild distortions in the applied impulse that will result in similar levels of voltage occurring at different lengths of time. Despite this as statistical similarity is likely to be present between all samples the data can be combined for CPF analysis.

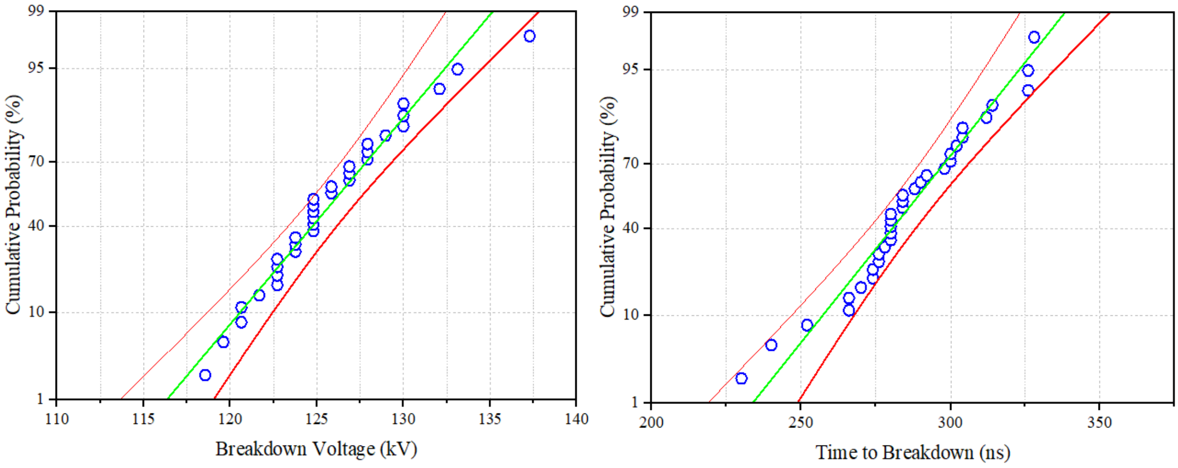


(a) (b)

Figure 6-26; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of mineral oil in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltage calculated for each of the three 'Elevated humidity' mineral oil samples when the fluid was exposed to negative nanosecond impulse are shown in Figure 6-26a. As outlined in the previous sections discussing the testing of the mineral oil under negative polarity nanosecond impulse (Section 6.2, 6.2.1.1 and 6.2.2.1), the nominal output voltage of the impulse circuit had to be increased from 150kV to 175kV to achieve breakdown of the fluid. In spite of this increase, breakdown of the mineral oil under negative nanosecond impulse still frequently took place on the plateau of the voltage impulse. Subsequently, no difference exists between the average values of breakdown voltage calculated, with each sample returning a value of 157kV. Therefore, it can again be assumed that no statistical difference may exist between the breakdown voltages of each sample.

The average time to breakdown of the ‘Elevated humidity’ mineral oil when stressed with nanosecond impulses of negative polarity are shown in Figure 6-26b. Even though no difference exists in the average breakdown voltage of each sample (Figure 6-26a), a 12% dissimilarity is present in the longest and shortest values of time to breakdown, calculated for Sample 1 (827ns) and Sample 2 (731ns) respectively. This results from breakdown of the fluid taking place on the plateau of the energising impulse where a minimal change in voltage will occur over a long timescale. It is clearly evident that breakdown occurs at such a point on the impulse as the average values of time to breakdown calculated for each mineral oil sample are much higher than the nominal rise-time of the impulse (400ns). Despite the aforementioned numerical difference between sample averages, as the confidence intervals overlap all samples can be assumed to exhibit a statistically similar time to breakdown.



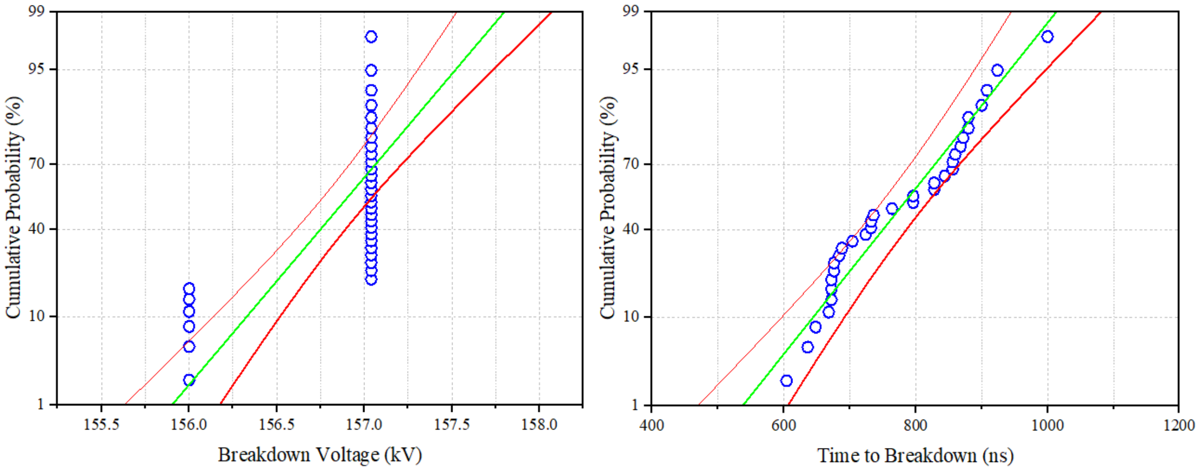
(a)

(b)

Figure 6-27; *Probability plots for 'Elevated humidity' mineral oil; CPFs for positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained during the stressing of the ‘Elevated humidity’ mineral oil with positive polarity nanosecond impulse was used to produce the CPF shown in Figure 6-27a. Breakdown of the fluid is seen to occur multiple times at voltage levels between 121kV and 130kV, with the greatest number of these taking place at a 125kV (20% of all recorded breakdown events). Despite this, the experimental data was still shown to be of normal distribution by the KS normality test (p-value 0.52). Consequently it was possible to extract the levels of voltage that correspond to a 10%, 50% and 95% probability of breakdown of the 'Elevated humidity' mineral oil when stressed with positive nanosecond impulse. These values of voltage are predicted by the CPF to be 121kV ($V_{10\%}$), 126kV ($V_{50\%}$) and 132kV ($V_{95\%}$).

The CPF produced from the time to breakdown data collected during the testing of the 'Elevated humidity' mineral oil again shows multiple breakdowns at particular values of time. However, unlike the breakdown voltage this only occurs twice in the time to breakdown data at 280ns and 284ns, accounting for 13% and 10% of breakdown events respectively. Again, this does not adversely affect the distribution with the data shown to be of normal distribution returning a goodness of fit coefficient of 0.78. As can be seen from the CPF (Figure 6-27b) the data is in excellent agreement with the predicted distribution, with all data points contained within the confidence bands and sitting on, or close, to the reference line. Therefore, the values of time to breakdown required to cause a 10%, 50% and 95% probability of breakdown were taking from the CPF; 257ns, 286ns, 323ns respectively.



(a) (b)

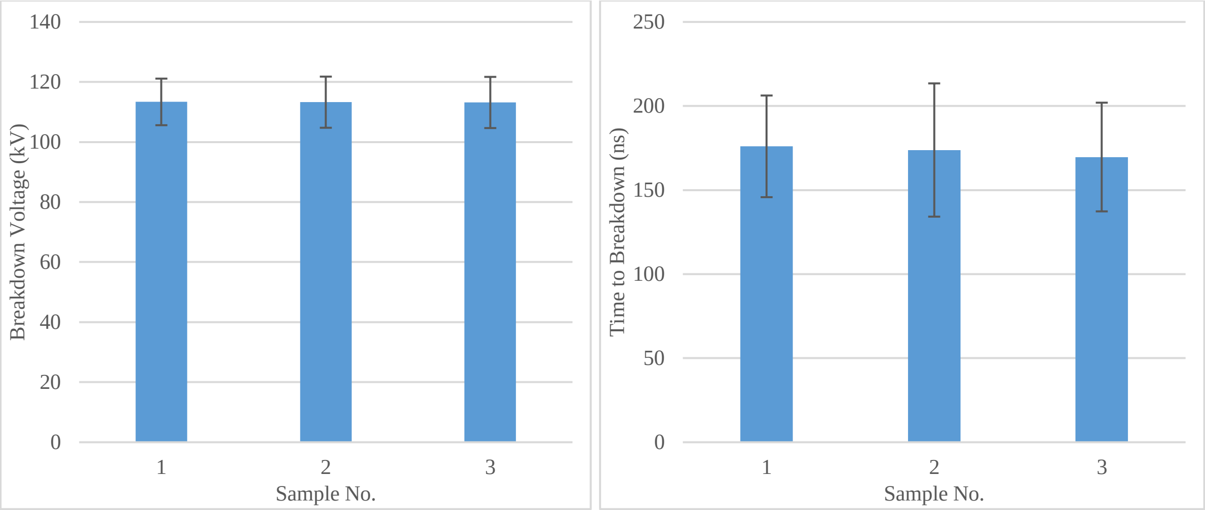
Figure 6-28; *Probability plots for 'Elevated humidity' mineral oil; CPFs for negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

Figure 6-28a validates that breakdown voltage data measured when the 'Elevated humidity' mineral oil samples were stressed with negative nanosecond impulse is not distributed normally, with breakdown occurring at either 156kV (20% of all breakdowns) or 157kV (80% of all breakdowns). This non-conformance to a normal distribution was confirmed through application of the KS normality test (p-value <0.01). Thus, the levels of voltage that would result in breakdown of the 'Elevated humidity' mineral oil under negative nanosecond impulse cannot be extracted from the CPF.

The time to breakdown data measured when the 'Elevated humidity' samples of mineral oil were stressed with nanosecond impulses of negative polarity was shown to be distributed normally (p-value 0.53). The data is seen to deviate from the distribution reference line at the 30th percentile and again at the 70th, however all data is contained within the confidence banding and, as aforementioned, does conform to the expected distribution. The values of time to breakdown predicted by the CPF to result in a 10%, 50% and 95% probability of breakdown of the 'Elevated humidity' mineral oil are 644ns, 775ns and 943ns respectively.

6.2.3.2. Breakdown of synthetic ester in the 'Elevated humidity' condition

The following section presents and discusses the experimental work involving samples of the synthetic ester MIDEL 7131 when in the 'Elevated humidity' condition (relative humidity 72%). When the experimental breakdown voltage and associated time to breakdown of the fluid was examined it was clear that over the test series no increase or decrease of the breakdown parameters occurred. That is to say, that no obvious trend exists in the data to suggest that the dielectric performance of the fluid is affect by exposure to multiple breakdowns. Thus, it is possible to group the data collected for each sample to create six datasets (three for a given impulse polarity) to be used in mean value evaluation.

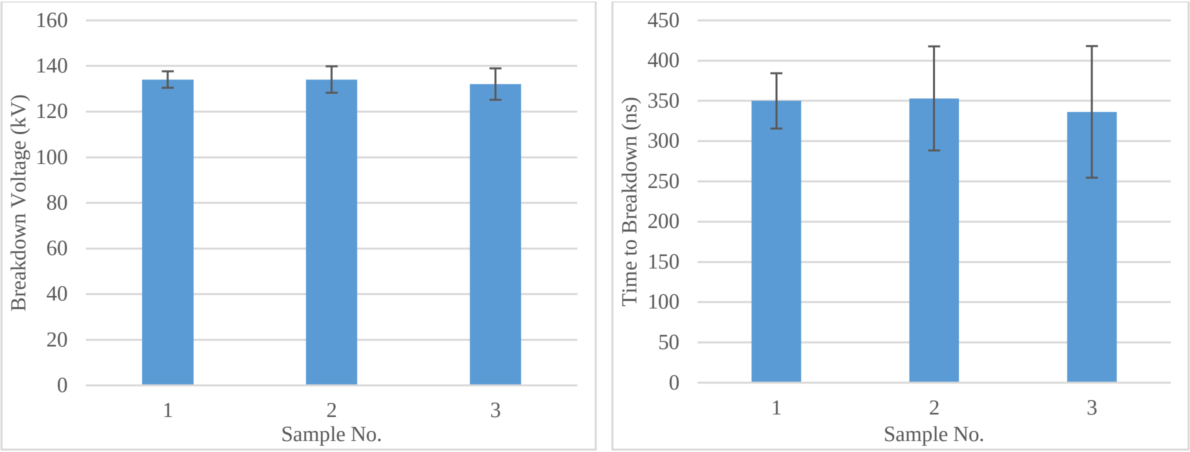


(a) (b)

Figure 6-29; *Positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages calculated for the 'Elevated humidity' samples of synthetic ester placed under positive nanosecond impulse stress are shown in Figure 6-29a. From the data it can be seen that all samples may possess statistical similarity in the level of voltage necessary for breakdown of the liquid to occur. This can be assumed given that the confidence intervals overlap in all case; also allowing for the pooling of the sample data to be used in CPF analysis.

Average values of time to breakdown associated with the breakdown of the 'Elevated humidity' synthetic ester samples stressed with positive polarity nanosecond impulse are shown above (Figure 6-29b). Identical behaviour exists in the time to breakdown as was observed in the breakdown voltage, with Sample 1 requiring the longest time to breakdown (176ns) and Sample 3 the shortest (170ns). This represents a slightly larger difference in time to breakdown than exists in breakdown voltage (3% as compared with only 1%). Again, this can be attributed to a wider spread of the time to breakdown data, which is evident in the larger error bars associated with the data. Given the size of the confidence intervals, which overlap in all cases, it can be said that statistical difference between the mean values of time to breakdown for each sample is unlikely.

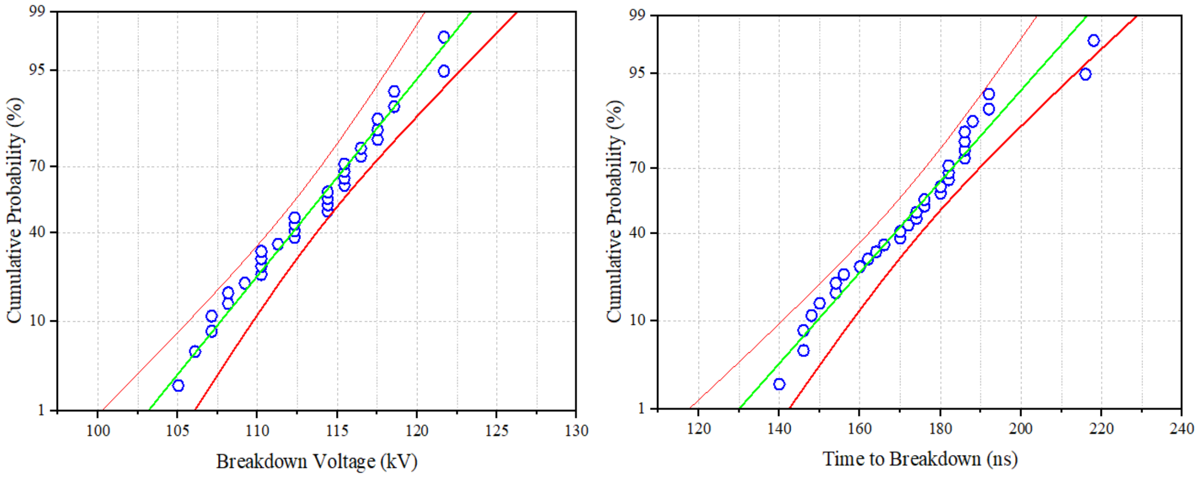


(a) (b)

Figure 6-30; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of synthetic ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The negative polarity breakdown voltage of the 'Elevated humidity' synthetic ester when under nanosecond impulse stress has been given above (Figure 6-30a). Any difference in the average values of breakdown voltage calculated for the liquid samples is unlikely to be statistically significant as the 95% confidence error bars overlap for all samples. It is therefore possible to group the data measured for each sample into a single dataset to facilitate cumulative probability analysis.

The average time to breakdown calculated for each of the synthetic ester samples under negative polarity nanosecond impulse show a likelihood of statistical similarity existing between all samples (Figure 6-30b). While this is identical to the observations made for the breakdown voltage data the numerical difference between average values of time to breakdown is higher (5% as compared with 2% for the breakdown voltage). This can be explained by the existence of outlying data points in the datasets associated with both Sample 2 and Sample 3. This is clearly evident given the large size of the 95% confidence interval calculated for the aforementioned samples and is confirmed when examining the CPF (Figure 6-31b).

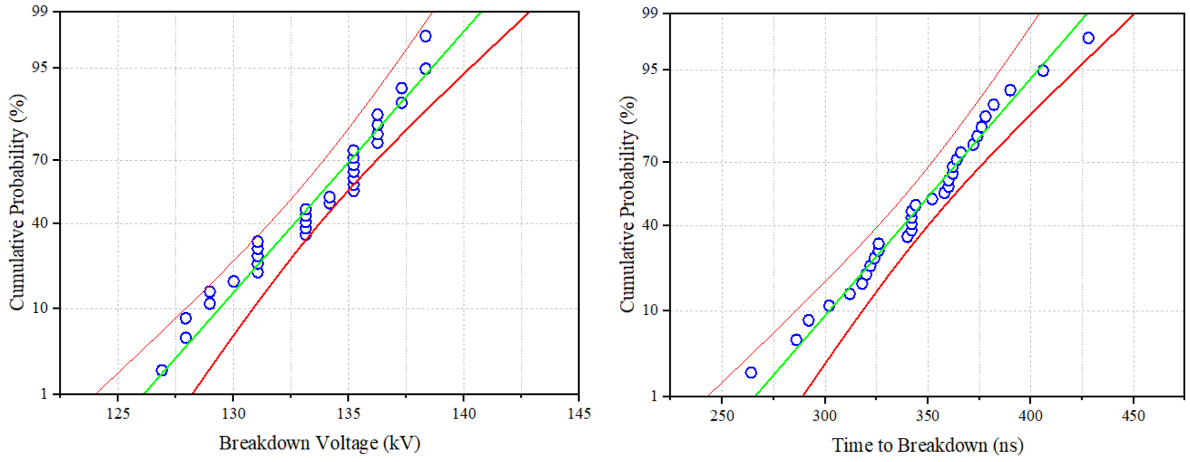


(a) (b)

Figure 6-31; *Probability plots for 'Elevated humidity' synthetic ester; CPFs for positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

Form the CPF produced from the data pertaining to the breakdown voltage of the ‘Elevated humidity’ synthetic ester under positive nanosecond impulse stress (Figure 6-31a) it can be seen that multiple breakdowns of the fluid occur at a number of voltage levels. At least two or more breakdowns occur at voltages ranging from 107kV to 118kV, with breakdown most commonly taking place at four different voltage levels, 110kV, 112kV, 114kV and 115kV, which each account for 13% of all breakdown events. Regardless of this, the experimental data was confirmed to be of normal distribution, returning a p-value from the KS normality test of 0.74. Given this conformance to a normal distribution, it is possible to extract the levels of voltage predicted by the CPF to result in a 10%, 50% and 95% probability of liquid breakdown, with these shown to be 108kV, 113kV and 120kV respectively.

The time to breakdown measured when the synthetic ester was stressed with positive nanosecond impulse was used to generate the CPF shown in Figure 6-31b. As with breakdown voltage, multiple breakdowns of the fluid are seen to occur for a given time. Although unlike the data in Figure 6-31a (breakdown voltage), multiple breakdowns are only observed for two specific times, namely, 182ns and 186ns which account for 10% and 13% of breakdowns respectively. Again, this does not affect the distribution of the experimental data with the data achieving a p-value of ~1. Given such a high goodness of fit coefficient, it is of no great surprise that the data fits well with the predicted distribution with 97% of the data contained within the confidence bands and 80% residing on the distribution reference line. Thus, extraction of the time to breakdown values which correspond to a 10%, 50% and 95% likelihood of breakdown was possible; with the CPF predicting these to be 141ns ($t_{10\%}$), 173ns ($t_{50\%}$) and 204ns ($t_{95\%}$).



(a)

(b)

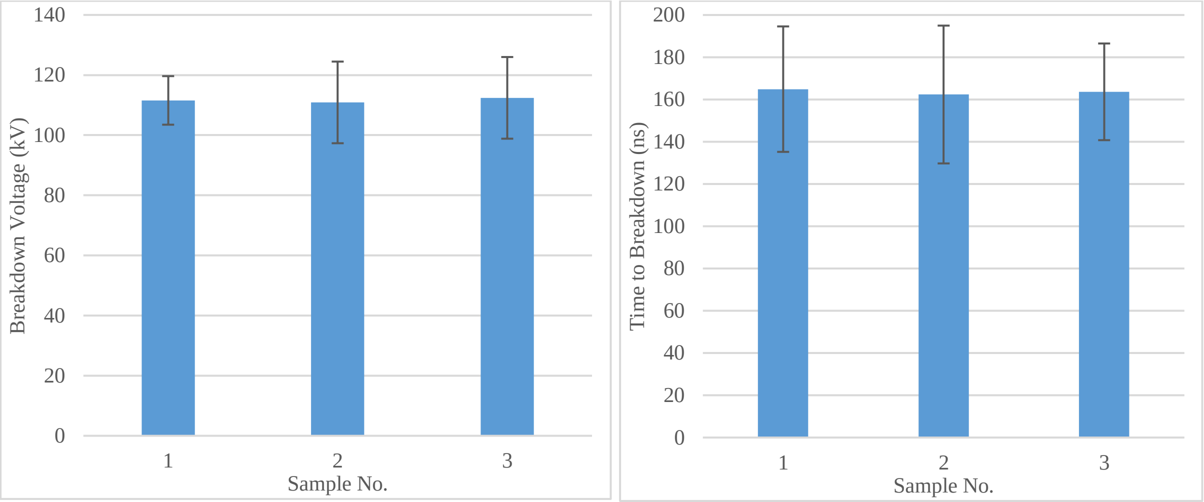
Figure 6-32; *Probability plots for 'Elevated humidity' synthetic ester; CPFs for negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data collected during the testing of the ‘Elevated humidity’ synthetic ester under negative polarity nanosecond impulse was subjected to the KS normality test. The data was shown to be distributed normally, returning p-value of 0.26. From Figure 6-32a, it is clear that multiple breakdowns occurred at given voltage levels, ranging from 131kV to 136kV. Multiple breakdowns most commonly occur at 135kV, which accounts for 23% of all breakdowns of the ‘Elevated humidity’ synthetic ester under negative nanosecond impulse. Nevertheless, the data is normally distributed and therefore it is possible to extract the predicted levels of breakdown voltage at all percentiles of interest. These were shown by the CPF to be 129kV ($V_{10\%}$), 133kV ($V_{50\%}$) and 139kV ($V_{95\%}$).

The time to breakdown data obtained when the ‘Elevated humidity’ synthetic ester was exposed to nanosecond impulses of negative was used to create the CPF in Figure 6-32b. This data underwent the KS normality test and proved to be of normal distribution (p-value ~1). Given this high goodness of fit coefficient it is to be expected that the experimental data agrees well with the distribution reference, which is evident from Figure 6-32b. Unlike the breakdown voltage data (Figure 6-32a), the time to breakdown data points are evenly distributed along the reference line, with all data contained within the confidence banding. The values of time to breakdown predicted to result in a 10%, 50% and 95% breakdown probability are 302ns, 347ns and 404ns respectively.

6.2.3.3. Breakdown of natural ester in the 'Elevated humidity' condition

The proceeding section presents data and provides discussion on the breakdown of the natural ester Envirotemp FR3 when in the 'Elevated humidity condition (relative humidity 73%) when stressed with nanosecond impulse voltage (rise-time 400ns) of both positive and negative polarity. Upon inspection of the experimental data obtained on the breakdown voltage and time to breakdown of the fluid it became clear that no discernible upward or downward trend existed in either breakdown parameter, irrespective of the impulse polarity. This facilitated the grouping of the ten breakdowns experienced by each sample into six datasets, three for a given polarity of impulse, to perform mean value analysis.

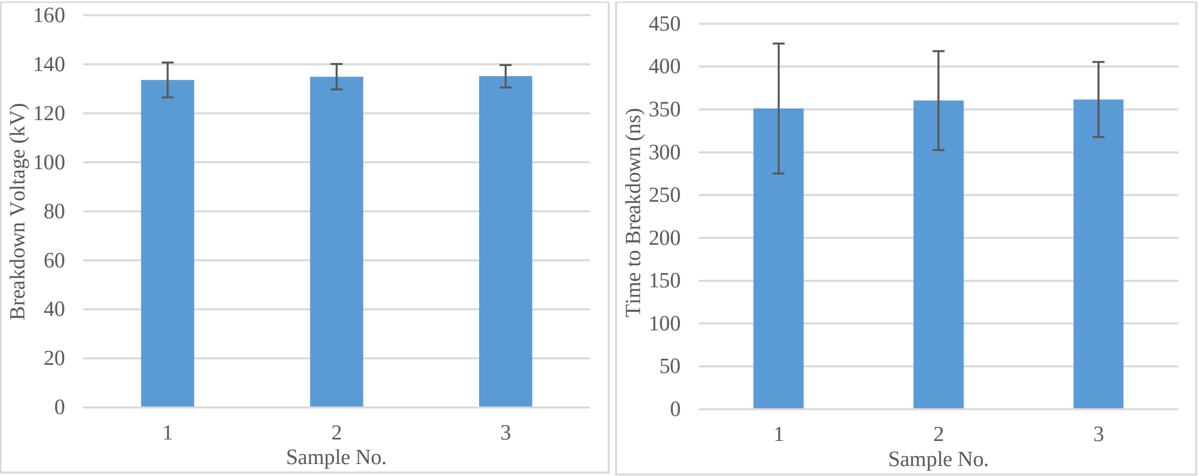


(a) (b)

Figure 6-33; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average breakdown voltages calculated for each of the three 'Elevated humidity' natural ester samples when stressed with nanosecond impulse of positive polarity are presented in Figure 6-33a. From the figure, it is obvious that all sample confidence intervals overlap and thus samples may possess a statistically similar dielectric strength. Breakdown of the fluid takes place over a narrow range of values with only a ~1% difference in the sample-to-sample averages. However, given that all samples may have a statistically similar breakdown voltage, shown by the overlapping confidence intervals, grouping of the experimental data into one large dataset for the purpose of CPF analysis is possible.

As with breakdown voltage of the natural ester under positive voltage stress (Figure 6-33a), statistical difference may not exist in the time required to result in breakdown of the fluid, again assumed due to the overlap in the 95% confidence intervals. That said, a slightly larger difference in the time to breakdown averages is observed than was the case with breakdown voltage (~2% as compared with 1%). This can be attributed to the wider spread of the time to breakdown data associated with the samples, evident from the much larger error bars present in this data.

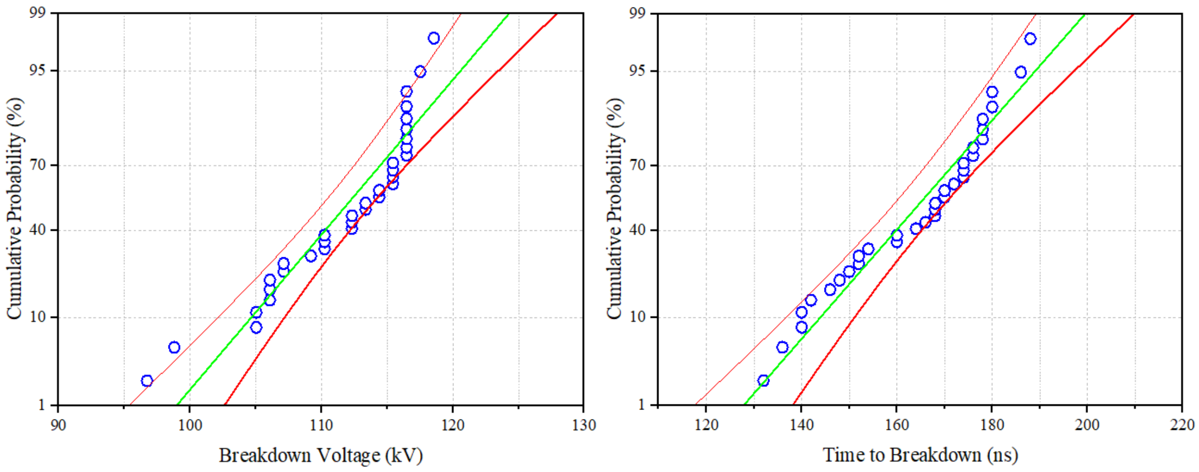


(a) (b)

Figure 6-34; *Negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of natural ester in 'Elevated humidity' condition. Each column is the mean of ten individual breakdown events, with error bars showing 95% confidence intervals.*

The average negative polarity breakdown voltage calculated from the experimental data obtained when stressing the 'Elevated humidity' natural ester with nanosecond impulse is given above (Figure 6-34a). There again is a likely absence of any statistically significant difference in the average breakdown voltages calculated for each of the three liquid samples given the overlapping of the 95% confidence intervals.

The average time to breakdown calculated for each of the natural ester samples when placed under negative nanosecond impulse stress shows identical behaviour to that of the breakdown voltage; with the longest time to breakdown calculated for Sample 3 (362ns) and the shortest Sample 1 (351ns). However, it must be said that this ~3% difference is unlikely to be of statistical significance given the overlapping of all 95% confidence intervals. The time to breakdown does differ from the breakdown voltage in that a larger difference exists between the highest and lowest average values (~3% as compared with 1%). This dissimilarity is attributed to datasets containing breakdowns that took place near the plateau of the impulse, evident when examining the CPF in Figure 6-36b, where a similar voltage could occur at a much longer time; this is evident in the larger error bars associated with the time to breakdown data as compared with those of the breakdown voltage.

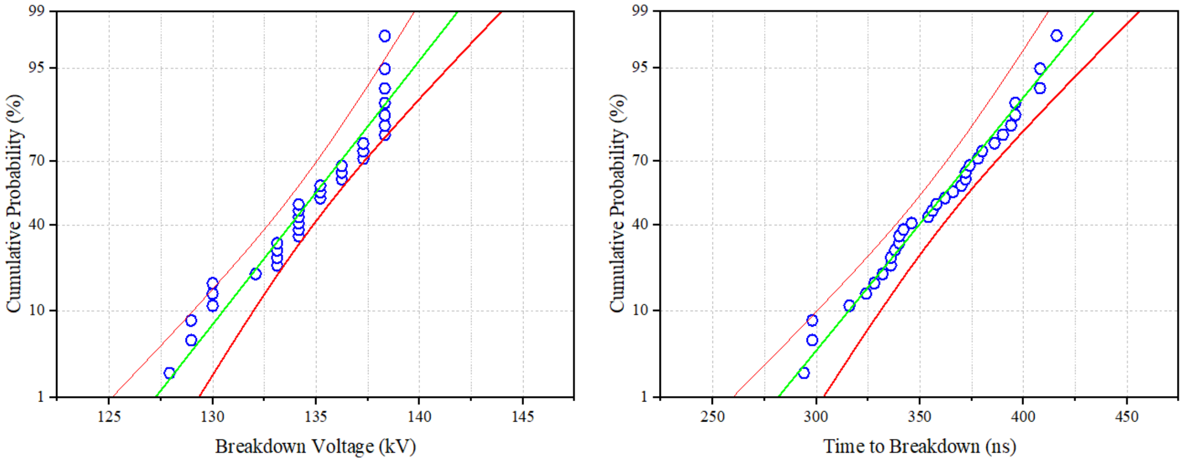


(a) (b)

Figure 6-35; *Probability plots for 'Elevated humidity' natural ester; CPFs for positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown.*

Breakdown voltage data obtained from stressing the ‘Elevated humidity’ natural ester with positive polarity nanosecond impulse was confirmed to be distributed normally, returning a goodness of fit coefficient of 0.36. From Figure 6-35a, it is evident that multiple breakdowns occur between 105kV to 116kV. These multiple breakdowns occurs most consistently at 116kV, accounting for 23% of all observed breakdown events. Nevertheless, the data was confirmed to be normally distributed and thus it is possible to extract the predicted levels of voltage to result in a 10%, 50% and 95% probability of breakdown. These were projected by the CPF to be 105kV ($V_{10\%}$), 112kV ($V_{50\%}$) and 121kV ($V_{95\%}$).

From the time to breakdown data obtained when the 'Elevated humidity' natural ester samples were stressed with nanosecond impulses of positive polarity the CPF shown in Figure 6-35b was generated. The experimental data was subjected to the KS normality test and subsequently confirmed to be normally distributed (p-value 0.35). Unlike the data in Figure 6-35a (breakdown voltage), the time to breakdown data points are evenly distributed along the reference line, with all data contained within the confidence bands. From the CPF values of time to breakdown predicted to result in a 10%, 50% and 95% probability of fluid breakdown are 134ns, 153ns and 178ns respectively.



(a) (b)

Figure 6-36; *Probability plots for 'Elevated humidity' natural ester; CPFs for negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown.*

The breakdown voltage data obtained when the 'Elevated humidity' natural ester was under negative polarity nanosecond impulsive voltage stress was shown by the KS normality test to be of normal distribution (p-value 0.73). Again, it was observed that multiple breakdowns occur at specific levels of voltage. Between 129kV and 138kV multiple breakdowns of the fluid can be seen at 129kV, 130kV, 133kV, 134kV, 135kV, 136kV, 137kV and 138kV. The most common level of negative voltage shown to cause breakdown of the 'Elevated humidity' natural ester was 138kV, which was responsible for 23% of all measured breakdowns. The data however was still confirmed by the KS normality test to be of normal distribution and therefore is it possible to extract the levels of voltage predicted by the CPF to result in a 10% (131kV), 50% (135kV) and 95% (140kV) probability breakdown.

The time to breakdown of the ‘Elevated humidity’ natural ester when the liquid was stressed with negative polarity nanosecond impulse voltage is also of normal distribution; confirmed by the KS normality test with the data returning a near perfect p-value of ~1. Given this, it is to be expected that the experimental data is in excellent agreement with the predicted distribution. From the CPF, shown in Figure 6-36b, the times predicted to result in a 10%, 50% and 95% probability of breakdown of the natural ester are 316ns, 358ns and 412ns respectively.

6.2.3.4. Summary of breakdown of dielectric liquids in the ‘Ambient humidity’ condition

The previous sections of this thesis (Section 6.2.3.1 to 6.2.3.3) presented and discussed the breakdown of the dielectric liquids when in the ‘Elevated humidity’ condition. This state of relative humidity represents the highest moisture content investigated within the work presented in this thesis (relative humidity >70%). Liquid samples were stressed with nanosecond impulses of positive and negative polarity until breakdown occurred. Obtained experimental data was analysed and it was shown that no discernible upward or downward trend in breakdown voltage, or associated time to breakdown, existed in the data collected for any liquid sample; irrespective of energisation polarity. Assessment of this data demonstrated that statistical difference is unlikely to exist in the breakdown parameters of the three samples for a given liquid and impulse polarity; facilitating the grouping of the datasets into a larger pool for the means of cumulative probability analysis. Calculated values of the chosen breakdown parameters derived from both the mean and CPF analysis have been summarised in Table 6-3.

Table 6-3; *Average breakdown voltage and time to breakdown of the 'Elevated humidity' dielectric fluids when stressed with 0.4μs impulse*

Breakdown Voltage					
	Liquid	V_{mean} ± 95% CI	$V_{10\%}$	$V_{95\%}$	*P-values*
Positive impulse	Shell Diala S4	126 ± 6.9kV	121kV	132kV	0.52
	MIDEL 7131	113 ± 7.4kV	108kV	120kV	0.74
	Envirotemp FR3	112 ± 9.3kV	105kV	121kV	0.36
Negative impulse	Shell Diala S4	157 ± 0.7kV	N/A	N/A	<0.01
	MIDEL 7131	133 ± 5.4kV	129kV	139kV	0.26
	Envirotemp FR3	135 ± 5.3kV	131kV	140kV	0.73
Time to breakdown					
	Liquid	t_{mean} ± 95% CI	$t_{10\%}$	$t_{95\%}$	*P-values*
Positive impulse	Shell Diala S4	286 ± 38ns	257ns	323ns	0.78
	MIDEL 7131	173 ± 32ns	149ns	204ns	~1
	Envirotemp FR3	164 ± 26ns	144ns	189ns	0.35
Negative impulse	Shell Diala S4	775 ± 174ns	644ns	943ns	0.53
	MIDEL 7131	347 ± 59ns	302ns	404ns	~1
	Envirotemp FR3	358 ± 56ns	316ns	412ns	~1

Under positive polarity nanosecond impulse the mineral oil exhibits a likelihood of having a statistically similar dielectric strength to both the synthetic and natural ester fluids; which are also seen to likely possess statistically similar breakdown strengths. This is however is not the case when the negative nanosecond impulse was applied to the fluids, with the mineral oil now found to have statistically higher breakdown strength than both ester fluids. Given that under negative energisation the breakdown of the mineral oil was only possible when the nominal peak amplitude of the voltage impulse was increased from 150kV to 175kV this is to be expected. When placed under negative impulse stress, both ester fluids again are assumed to have a statistically similar breakdown performance.

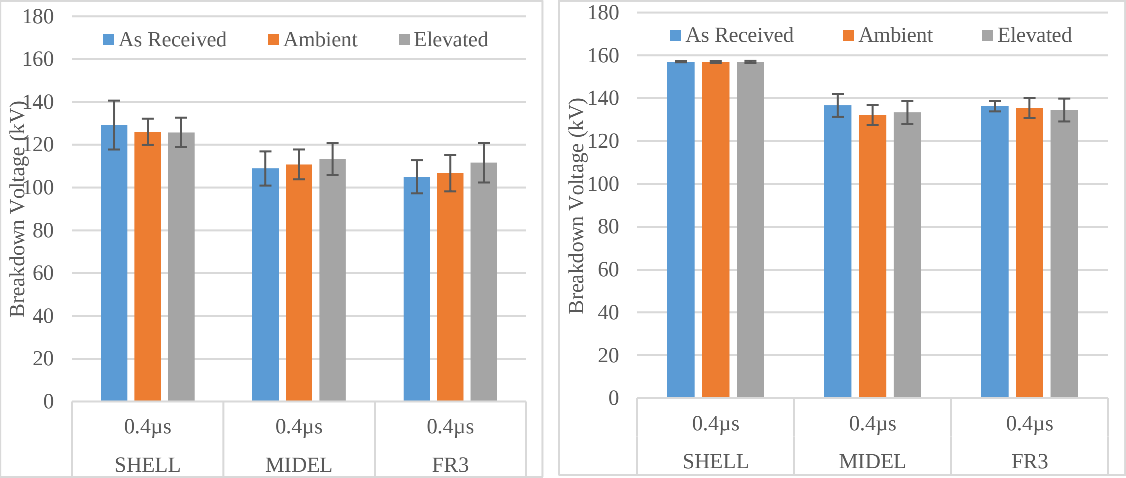
The time to breakdown of the dielectric fluids when under positive nanosecond impulse does not show the same behaviour as that of the breakdown voltage, with the mineral oil now seen to require a statistically longer time to breakdown; ~1.7 times that of the synthetic ester and natural ester fluids. Again, the ester fluids exhibit similar performance, with both dielectric liquids seen to require a time to breakdown that is likely absent of statistical difference when the impulse is of positive polarity. Under negative energisation the mineral oil again shows the best breakdown performance, once more requiring a statistically longer time to breakdown than both the synthetic ester and natural ester fluids. The time to breakdown of the mineral oil is seen to be ~2.2 times longer than that of the ester fluids, regardless of the need to increase the peak amplitude of the voltage impulse (raised from 150kV to 175kV). This highlights that irrespective of impulse polarity the mineral oil offers significantly better dielectric performance than both synthetic ester and natural ester fluids under nanosecond impulse voltage stress.

Under positive nanosecond impulse the CPF analysis predicts that the mineral oil will require a higher level of breakdown voltage at all percentiles of interest; as much as 12% and 13% greater than the synthetic ester and natural ester respectively. The breakdown of the mineral oil is predicted to occur over a narrower range of values than both ester fluids; demonstrating that under the testing conditions applied (described in Section 3.6.1) mineral oil offers better dielectric strength as well as a more consistent performance than both ester fluids. When the impulse is of negative polarity it is now not possible to predict the levels of voltage that will result in the breakdown of the mineral oil, due to the failure of the data to conform to a normal distribution. Breakdown of the natural ester is higher than the synthetic ester at all percentiles of interest, however only by 2% with both fluids predicted to have very similar breakdown performance under negative polarity nanosecond impulse.

The values of time to breakdown predicted by the CPF when the impulse is of positive polarity follow an identical trend to that predicted for the breakdown voltage. The mineral oil is predicted to require the longest time to breakdown at all percentiles of interests, as much as 1.7 times that of the synthetic ester and ~1.8 times greater than the natural ester. Predicted values of time to breakdown are similar for both ester fluids; however, the synthetic ester does require as much as 8% longer to breakdown than the natural ester. The spread of predicted values is largest in the data associated with the breakdown of the mineral oil, with the breakdown of the natural ester predicted to occur over the narrowest range. The longest values of time to breakdown when under negative voltage stress are again predicted for the mineral oil and the synthetic ester the shortest. The CPF predicts that under negative energisation the mineral oil will require as much as ~2.3 times longer to breakdown than both ester fluids. The range of predicted times at which the breakdown of the mineral oil will occur again span the widest range, with those associated with the synthetic ester the narrowest. The behaviour observed for the ester fluids is in contrast to what was predicted by the CPF when the impulse was of positive polarity; demonstrating that when the impulse is negative the natural ester offers a higher dielectric strength to the synthetic ester but at a cost of a less predictable breakdown performance.

6.3. Summary of breakdown under 0.4μs rise-time impulse

This chapter of the thesis focused on the presentation of discussion of experimental work involving the three chosen dielectric liquids (Shell Diala S4 mineral oil, MIDEL 7131 synthetic ester and Envirotemp FR3 natural ester) in three discrete states of relative humidity (‘As Received’, ‘Ambient humidity’ and ‘Elevated humidity’). Samples of each of the chosen liquids in the given states of relative humidity were stressed with the so called ‘nanosecond impulse’ (nominal rise-time 0.4μs) of both positive and negative polarity. The samples underwent ten separate breakdown events with breakdown voltage and time to breakdown recorded. This data was then subjected to both mean value and cumulative probability analysis.



(a) (b)

__Figure 6-37;__ (a) Positive and (b) negative 0.4μs impulse breakdown voltage of the mineral oil, synthetic ester and natural ester in the three discrete levels of relative humidity. Each column is the mean of thirty individual breakdown events, with error bars showing 95% confidence intervals.

When evaluating measured breakdown voltage (Figure 6-37a) for liquid samples stressed with positive nanosecond impulse, it is evident that there is unlikely to exist any statistically significant difference in levels of breakdown voltage recorded for a given dielectric liquid as relative humidity is increased. This again supports the observation that the dominant breakdown mechanism is one of ionisation front (streamer) development within the volume of the fluid. This type of breakdown has been shown to be highly resilient to the presence of contaminants, such as moisture and particulate matter, within the dielectric liquid [16], [82]. The dominance of the ionisation mechanism, as opposed to one of electrostriction (bubble formation), in the breakdown of dielectric liquids under short-duration impulse voltage has been confirmed in a number of experimental as well as analytical studies [13], [14], [69], [70]. This was also discussed by Atrazhev et al. in [147] where the breakdown processes under a number of impulses were evaluated analytically. The authors propose that for impulses of rise-time <0.5μs the likely mechanism for breakdown of dielectric liquid is the development and propagation of ionisation fronts, with breakdown under longer impulses (>0.5μs) dominated by bubble formation from joule heating and liquid evaporation that leads to the development of low-density regions (bubbles). When the complete dataset (all investigated humidity levels) of each liquid is compared against the others it is again unlikely that statistical difference exists in positive breakdown voltage. This is not the case when examining the data for a given humidity level in isolation. When this approach is applied clear, statistical, difference exists between the levels of breakdown voltage recorded for the two ester fluids and the mineral oil; with this fluid clearly seen to exhibit statistically higher levels of breakdown voltage in both the ‘As Received’ and ‘Ambient humidity’ conditions. Breakdown of both ester fluids is seen to occur at what is likely to be a statistically similar voltage for all examined levels of relative humidity.

The first observation which can be made from the experimental data obtained when the liquid samples were stressed with negative impulse is that, in all test cases, breakdown of the mineral oil occurs at a significantly higher level than is seen for both ester fluids. This is as a result of the inability to achieve breakdown of the mineral oil under the selected energisation voltage (nominally 150kV) and the subsequent requirement to increase this voltage to a level of 175kV in order to achieve any breakdown of the liquid samples. Even with the increase in energisation voltage breakdown still did not occur on the rising edge of the impulse, rather on the plateau; consequently variation in measured values of breakdown voltage of the mineral oil is greatly reduced compared to that of breakdown occuring in an increasing dv/dt condition (as is seen under positive impulse stress). Again, relative humidity is seen to exert no influence on breakdown voltage, with a likely absence of statistical difference observed for a given liquid as humidity is increased. As aforementioned, this is due to the breakdown being dominated by ionisation front development rather than a process that relies on the creation of low-density regions (bubbles) within the liquid volume. As with the data under positive impulse, breakdown of the ester fluids occur at a statically similar level for all liquid samples irrespective of individual humidity levels.

Table 6-4; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under positive 0.4μs impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	329 ± 134ns	24.3km/s	41km/s	17.3km/s	3rd
	MIDEL 7131	162 ± 30ns	49.4km/s	60.6km/s	41.6km/s	3rd
	Envirotemp FR3	149 ± 31ns	53.7km/s	67.8km/s	44.4km/s	3rd
Ambient humidity	Shell Diala S4	293 ± 44ns	27.3km/s	32.1km/s	23.7km/s	3rd
	MIDEL 7131	165 ± 32ns	48.5km/s	60.2km/s	40.6km/s	3rd
	Envirotemp FR3	153 ± 25ns	52.3km/s	62.5km/s	44.9km/s	3rd
Elevated humidity	Shell Diala S4	286 ± 38ns	28km/s	32.3km/s	24.7km/s	3rd
	MIDEL 7131	173 ± 32ns	46.2km/s	56.7km/s	39km/s	3rd
	Envirotemp FR3	164 ± 26ns	48.8km/s	58km/s	42.1km/s	3rd

Table 6-5; *Time to breakdown of the three dielectric fluids and average streamer velocities measured under negative 0.4μs impulse stress. Nominal streamer mode is that corresponding to average streamer velocity.*

Condition	Liquid	t_{mean} ± 95% CI	Mean average velocity	Upper mean velocity	Lower mean velocity	Nominal streamer mode
As Received	Shell Diala S4	941 ± 307ns	8.5km/s	12.6km/s	6.4km/s	2nd/3rd
	MIDEL 7131	398 ± 57ns	20.1km/s	23.5km/s	17.6km/s	3rd
	Envirotemp FR3	394 ± 67ns	20.3km/s	24.5km/s	17.4km/s	3rd
Ambient humidity	Shell Diala S4	872 ± 240ns	9.2km/s	12.7km/s	7.2km/s	2nd/3rd
	MIDEL 7131	336 ± 48ns	23.8km/s	27.7km/s	20.8km/s	3rd
	Envirotemp FR3	368 ± 52ns	21.7km/s	25.3km/s	19.1km/s	3rd
Elevated humidity	Shell Diala S4	775 ± 174ns	10.3km/s	13.3km/s	8.4km/s	2nd/3rd
	MIDEL 7131	347 ± 59ns	23.1km/s	27.7km/s	19.7km/s	3rd
	Envirotemp FR3	358 ± 56ns	22.4km/s	26.5km/s	19.3km/s	3rd

Table 6-4 shows the average time to breakdown of the three dielectric liquids in each state of relative humidity when under positive nanosecond impulse stress. The table also shows the minimum average propagation velocity of breakdown streamers (calculated by dividing the inter-electrode gap distance by the average time to breakdown) and the upper and lower calculated velocities which are derived from the upper and lower average time to breakdown values. As no account has been taken of the statistical time (time for onset of the streamer), the velocities stated herein can be thought of as the minimum average velocities at which the streamer propagates through the gap. As with positive breakdown voltage, time delay to breakdown is seen to likely be statistically similar for a given liquid irrespective of the relative humidity of the test sample. Agreement with the breakdown voltage data is also seen in the ‘As Received’ and ‘Ambient humidity’ condition samples for which the mineral oil exhibits a statistically longer time to breakdown than both the synthetic ester and natural ester liquids. However, analysis of the time delay to breakdown under positive energisation (Table 6-4) does expose dissimilarities to the trends observed in the breakdown voltage data. There now exists a statistically significant difference in the values of time to breakdown measured for samples at the highest state of relative humidity (‘Elevated humidity’) with the mineral oil requiring a statistically longer time to breakdown than both ester fluids. The ester fluids exhibit a similar dielectric performance, with statistical difference unlikely to be present in the measured values of time to breakdown at any of the investigated levels of relative humidity. Interestingly, despite the statistical difference in time to breakdown of the mineral oil and ester fluids all liquids exhibit the development of similar, namely 3rd mode, streamer velocities. It can be said that at all levels of relative humidity positive streamers in mineral oil propagate ~50% slower than those in both the synthetic ester and natural ester fluids, with streamers in these liquids seen to move at very similar velocities. However, this can only be fully substantiated through further analysis were both statistical and formative time are taken into account. The lower propagation velocities of streamers in mineral oil is to be expected given the inability of ester fluids to hold off streamer acceleration coupled with the much lower acceleration voltages observed for these liquids compared to those of mineral oil [13], [15], [68].

Unlike the results obtained from positive impulse testing, time to breakdown under negative energisation agrees well with the trends in the breakdown voltage data with statistical difference unlikely in the measured time to breakdown for a given liquid irrespective of the relative humidity of the sample. Assessment of the average time to breakdown data obtained when the three dielectric fluids were stressed with negative nanosecond impulse, presented in Table 6-5, has shown that at all levels of relative humidity the mineral oil requires a statistically longer average time to breakdown than both ester fluids. This is a clear indication of the inability to achieve ‘overstressed’ (rising edge) breakdown of the mineral oil under negative nanosecond impulse; with time to breakdown values seen to universally exceed the nominal rise-time of the impulse (~400ns); demonstrating the advantageous characteristics of mineral oil under such short negative impulses. Streamer velocities under negative energisation are lower for each of the dielectric liquids than was observed under positive voltage stress; this is to be expected given the ionisation mechanism that drives streamer propagation under negative voltage. As aforementioned, the development of negative space charge in the region of the streamer will curtail the growth, and thus negative streamers usually propagate at a much slower rate than those driven by positive voltage [15]. Both ester fluids are observed to experience the development of streamers with the average velocities corresponding to the 3rd propagation mode at all levels of relative humidity, though with lower propagation velocities than when the liquids are under positive voltage stress (~25km/s as compared with as much as ~68km/s). The streamers developed in the mineral oil under negative nanosecond impulse are, in the most part, early-stage 3rd mode streamers, propagating at much slower velocities than those observed in the ester fluids. Velocities of ~13km/s are calculated for streamers in the mineral oil at all states of relative humidity; with some shown to propagate as slow as ~6km/s. This corresponds to the transition between 2nd and 3rd modes which is to be expected given the much higher voltages required to transition a streamer to the ‘faster’ modes within mineral oil [15].

In conclusion, the work presented and discussed in this chapter has shown that under both positive and negative nanosecond impulse the mineral oil offers greater dielectric performance than both synthetic ester and natural ester fluids. The chosen mineral oil exhibited a statistically higher breakdown voltage and time to breakdown than both ester fluids under both positive and negative voltage stress, even requiring an increase in the nominal amplitude of the applied impulse to achieve breakdown under negative energisation. Desirable breakdown characteristics were also observed for the mineral oil in relation to streamer development with the fluid able to resist the development of ‘faster’ 3rd mode streamers under negative voltage stress. Irrespective of energisation polarity streamers in mineral oil were as much as 50% slower moving than those propagating in the ester fluids; with these fluids offering very similar performance in terms of streamer development. In relation to the effect moisture content has on the observed dielectric performance of the fluids it can be said that irrespective of the energisation polarity the relative humidity of the fluid exerts no influence on the breakdown parameters (breakdown voltage and time to breakdown) of mineral oil, synthetic ester or natural ester when stressed with nanosecond impulse voltage.

Chapter 7 – Breakdown of liquid-solid composite insulation

7.1. Introduction

While it is important to understand the bulk breakdown characteristics of liquid dielectrics to allow such fluids to be used as the insulating medium for large electrical machines it does not fully represent the practical scenario. Within large electrical equipment, such as pulsed power machines, it is common for a composite insulation system to be in operation. These systems consist of liquid dielectric, acting as the bulk insulator and cooling medium, in direct contact with solid dielectric material. An example of such a composite system is that utilised within a power transformer, which consists of liquid insulation placed in direct contact with solid dielectric in the form of Kraft paper. Thus, the vast majority of research work in the area of liquid-solid composite breakdown has focused on the breakdown of liquid-solid insulating systems under the electrical stress commonly experienced within a power transformer. Typically, this will take the form of stressing composite systems formed of dielectric liquid and Kraft paper with either AC or standard lightning impulse voltages [135], [148]-[150]. However, in pulsed power machines Kraft paper is not commonly used, rather different solid polymers are employed for tasks such as providing mechanical support to the internal structure of the machine. Consequently, efforts must be made to increase understanding of the dielectric behaviour of solid polymer-insulating fluid interfaces stressed with HV impulses of characteristics more akin to those applied to pulsed power machines.

To that end, this chapter of the thesis will present an investigation conducted into the breakdown characteristics of composite insulating systems formed from the dielectric liquids studied in the previous chapters of this thesis and practical polymers currently, or proposed to be, used within pulsed power machines. Interfaces formed of the synthetic ester fluid, MIDEL 7131 (M&I Materials, UK) or the natural ester fluid, Envirotemp FR3 (Cargill, USA) and solid polymers (Nylon 6,6, PMMA, DELRIN and TORLON) were stressed with a number of discrete voltage impulses of positive and negative polarity as well as various wave-shapes, characterised by rise-times of 0.4μs, 1.2μs and 7μs; with all data measured against a benchmark of the same interfaces formed with a mineral oil (Shell

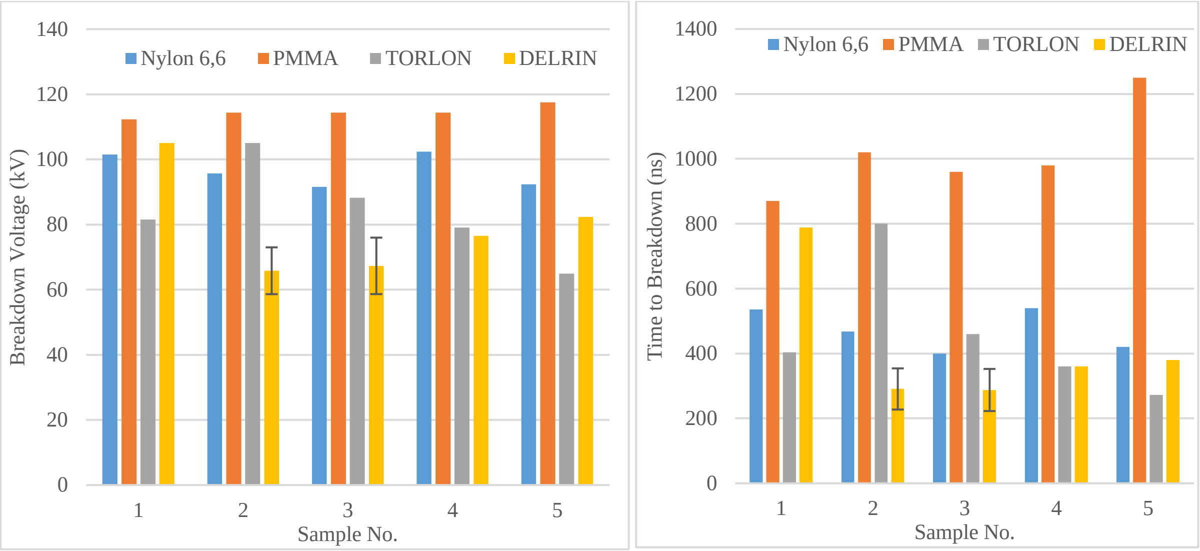
Diala S4). Each Liquid-polymer sample was tested in accordance with the methodology described in detail within Section 3.6.2. Briefly, the liquid-polymer composite samples (five for a given liquid-polymer pairing and impulse polarity) were subjected to HV impulse voltage with breakdown voltage and time to breakdown logged for either ten interfacial flashovers of the interface or one single bulk breakdown of the polymer dielectric. Application of this methodology will provide information on the level of voltage necessary to cause breakdown of the composite system as well as giving indication of the type of breakdown likely to be experienced by a given liquid-polymer combination. Firstly, experimental data obtained from stressing the liquid-polymer interfaces with a given impulse will be presented in isolation with a discussion of the possible mechanisms responsible from the observation made in each subsection provided within the summary at the end of the chapter (Section 7.5).

7.2. Breakdown of liquid-solid composite insulation under lightning impulse

The proceeding sections of this chapter focus on the breakdown of the liquid-composite insulation systems when stressed standard 1.2/50μs lightning impulse voltage. In order to ascertain what, if any, effect impulse polarity has on breakdown dynamics separate tests were conducted using positive and negative energisation. The composite systems investigated consist of the chosen practical polymers immersed in the three dielectric liquids, which are in the ‘As Received’ level of relative humidity. That is to say, the liquids have not been conditioned in any way, with the moisture content of the samples as was provided by the manufacturer (9% to 21% relative humidity). The decision to use fluids in this condition was influenced by the negligible effect that relative humidity had on the bulk breakdown performance of the fluids, shown throughout the experimental work discussed in Chapters 4-6 of this thesis. As aforementioned five samples of each liquid-polymer combination were tested for a given impulse polarity. The experimental data obtained pertaining to the breakdown voltage and time to breakdown of the liquid-polymer systems was subjected to mean value analysis where possible (when ten interfacial flashovers were observed) or simply stating the measured breakdown parameters in the case of a single breakdown of the polymer.

7.2.1. Breakdown of mineral oil-polymer composite insulation

Composite insulating systems formed of the mineral oil (Shell Diala S4) and the four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with standard lightning impulse voltage. As aforementioned, ten samples of each liquid-polymer combination were prepared to be used within the experimental work. Five samples were stressed with lightning impulse of positive polarity, while the remaining five samples were subjected to same impulse of negative polarity. Experimental data was obtained for the breakdown voltage and time to breakdown of each liquid-polymer sample with data analysed for mean values (when ten flashovers of the interface occurred) or simple stated if bulk breakdown of the polymer occurred.

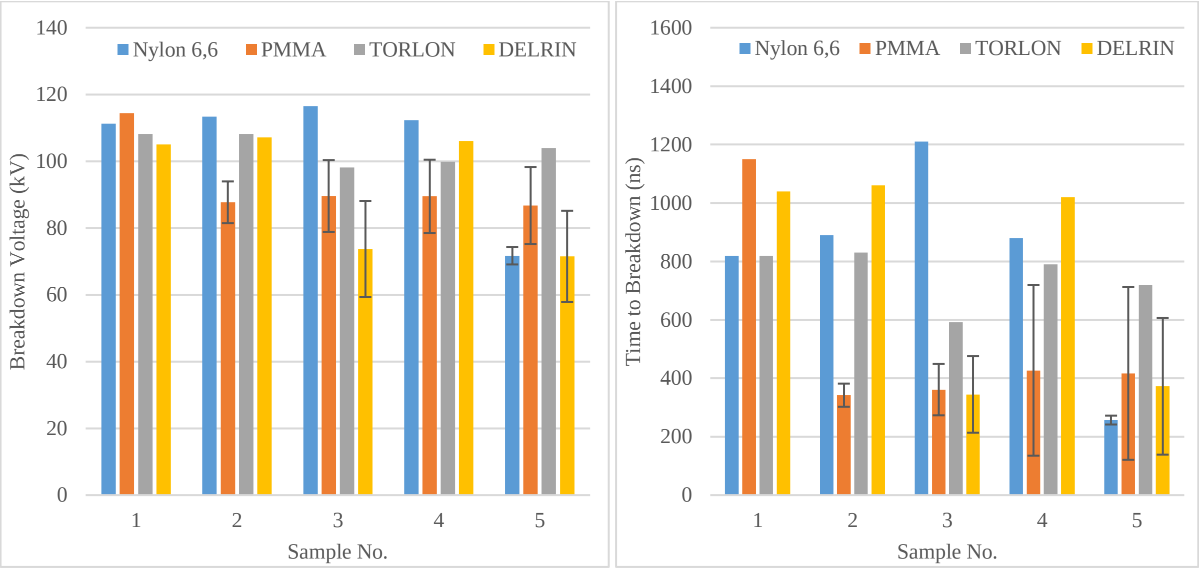


(a) (b)

Figure 7-1; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

The positive polarity lightning impulse breakdown voltage measured for each of the liquid-polymer combinations consisting of the chosen polymer dielectrics and mineral oil are shown in Figure 7-1a. Data relating to both interfacial flashover and bulk breakdown of the polymer dielectric is provided in the figure. Data devoid of error bars represents an insulation system that experienced bulk polymer breakdown, with all other data showing samples which underwent ten individual interfacial flashover events. The errors bars associated with the data represent the standard deviation in the breakdown voltage of the ten observed interfacial flashover events. From the breakdown voltage data provided in Figure 7-1a, it can be said that breakdown of the polymer dielectric consistently occurs at a higher voltage level than that of the surface flashover of the liquid-polymer interface. Bulk breakdown of the insulating systems which utilise the PMMA polymer exhibit the highest breakdown strength but clearly show a favourability for bulk breakdown of the polymer with this observed in 100% of tests. Bulk polymer breakdown was also seen to consistently occur for both the Nylon 6,6 interfaces as well as those formed with the TORLON polymer, though at a lower level of voltage than those insulating systems that consist of the mineral oil and PMMA polymer. The only combination of mineral oil-polymer system that experienced interfacial flashover was those utilising the DELRIN polymer, with this observed in 40% of the test samples. Flashover voltage of the mineral oil-DELRIN interface, given the overlapping error bars, can be assumed to occur at a statistically similar level for all samples and was significantly lower than when the bulk polymer breakdown was observed for the system (as much as 38% lower in the most extreme case).

When examining the time to breakdown measured for each of the mineral oil-polymer insulating systems it is evident that similar behaviour is observed to that discussed regarding the breakdown voltage of the systems. The liquid-PMMA interfaces again show the highest breakdown strength with these seen to require the longest time to breakdown, with polymer breakdown occurring in all tests. Interestingly though the variation in the time to breakdown of the each of the liquid-PMMA samples is seen to be greater than the difference in breakdown voltage of the samples. A difference of ~44% exists between the longest and shortest values of time to breakdown for the PMMA samples with only a 5% difference in the breakdown voltages of these samples. This is attributed to bulk breakdown of the polymer occurring near the peak of the impulse where voltage change will be minimal over a prolonged period. The largest sample-to-sample variation in time to breakdown was observed in the breakdown of the insulating systems using the TORLON polymer, all of which experienced bulk polymer breakdown; with the longest time to breakdown recorded for a sample ~3 times longer than the shortest (Sample 2 compared to Sample 5). This large difference is postulated to result from the varied propagation path of the streamer through the bulk of the polymer. Surprisingly, the shortest values of time to breakdown, measured for the fifth sample of the liquid-TORLON combination, are below that of the liquid-DELRIN samples that experienced interfacial flashover.



(a) (b)

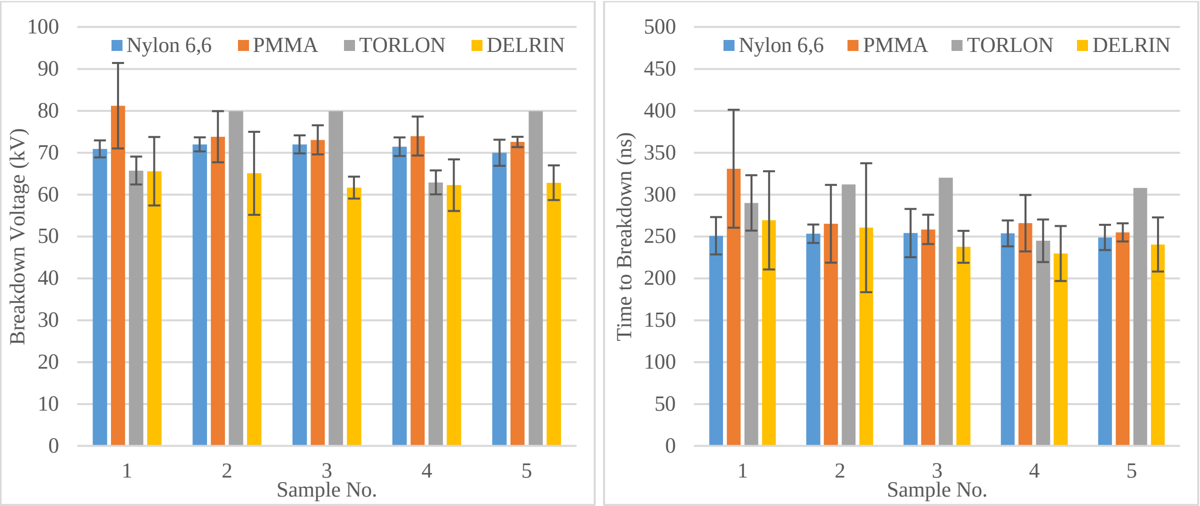
Figure 7-2; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

Figure 7-2a depicts the negative polarity breakdown voltage when the composite mineral oil-polymer insulating systems were stressed with lightning impulse. Again data which is absent of error bars represents test samples that underwent bulk breakdown of the polymer, with all others experiencing ten individual flashovers of the liquid-polymer interface. The first observation is that the mineral oil-PMMA polymer systems now favour interfacial flashover, as opposed to the bulk polymer breakdown seen under positive voltage stress. Breakdown of these liquid-PMMA systems no longer occurs at the highest level of voltage when bulk polymer breakdown occurs; with the highest breakdown strength now observed for the insulting systems which utilise the Nylon 6,6 polymer. However, when the breakdown takes place across the liquid-polymer interface the PMMA systems do offer the best (highest) dielectric strength, above that of the Nylon 6,6 and DELRIN systems which also experience interfacial flashover. That said, as the error bars of the data overlap this is unlikely to be of statistical significance. The probability of interfacial flashover occurring for a given liquid-polymer combination is seen in increase under negative impulse stress for both the PMMA and Nylon 6,6 systems, but for those which employ the TORLON and DELRIN polymers this probability remains unchanged from what was observed during positive polarity impulse tests. The likelihood of the flashover of the liquid-polymer interface is seen to be highest for the systems that use the PMMA polymer, occurring in 80% of tests, with those employing TORLON the lowest as these systems consistently experienced bulk breakdown of the polymer.

The time to breakdown measured when the chosen mineral oil-polymer combinations were placed under negative lightning impulse voltage stress are provided in Figure 7-2b. As with breakdown voltage the highest value of time to breakdown was measured for the liquid-Nylon 6,6 systems when bulk breakdown of the polymer occurred (Sample 3). As was observed with the data obtained from experiments using positive lightning impulse, the difference between the longest and shortest time to breakdown is much greater than that which exists between the highest and lowest breakdown voltages. The longest time to breakdown was more than twice that of the shortest, observed for Sample 3 of the Nylon 6,6 and TORLON polymers respectively, while the difference in breakdown voltages of these samples was only 19%. Both samples experienced bulk breakdown with the large difference attributed to the specific propagation path taken by the breakdown streamer. Further to this the breakdown of the aforementioned liquid-Nylon 6,6, sample took place at the peak nominal rise-time of the impulse, meaning the change in voltage would be minimal compared to the change in breakdown time. In all cases bulk breakdown of the polymer requires a longer time to breakdown than when interfacial flashover occurs. Again, there is a likely absence of statistical difference in the time to breakdown of any liquid-polymer system when interfacial flashover is observed.

7.2.2. Breakdown of synthetic ester-polymer composite insulation

The following section will present and discuss the experimental data obtained when composite insulating systems formed of the synthetic ester (MIDEL 7131) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with standard lightning impulse voltage. To ascertain the affect voltage polarity may exert on breakdown the composite samples were exposed to impulses of both positive and negative polarity (five samples of a particular composite system for a given impulse polarity). Data on the breakdown voltage and associated time to breakdown for the composite systems was obtained for the purpose of mean value analysis.

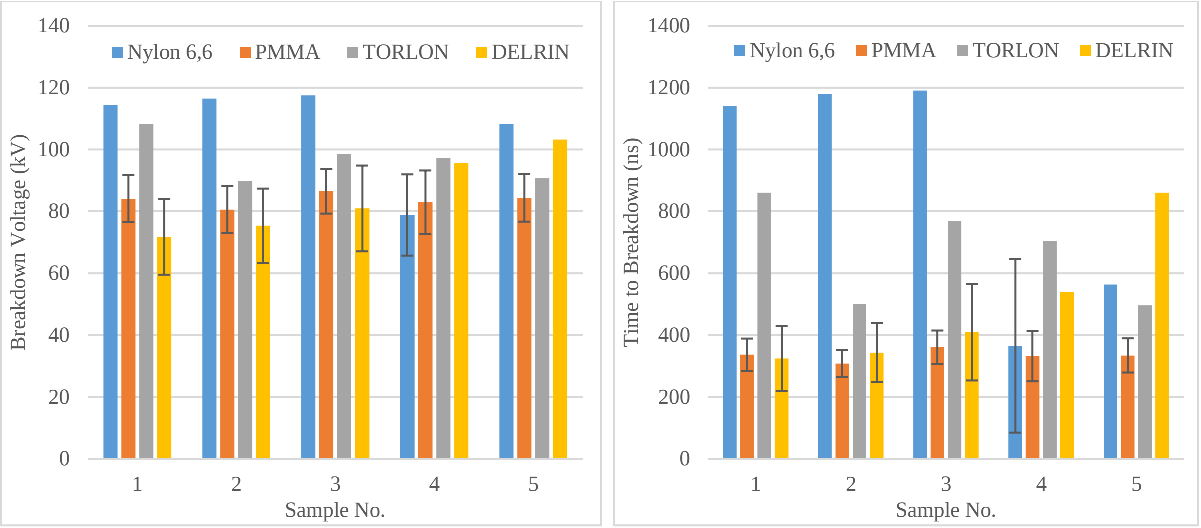


(a) (b)

__Figure 7-3;__ Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.

The breakdown voltage of the synthetic ester-polymer composite insulation samples when stressed with positive lightning impulse can be seen above (Figure 7-3a). From the data presented it is evident that composite systems utilising synthetic ester favour flashover of the liquid-polymer interface, as opposed to bulk breakdown of the polymer, with this form of breakdown occurring for all test samples involving Nylon 6,6, PMMA and DELRIN and 40% of those in which the TORLON polymer was used. When examining a given liquid-polymer combination, due to the overlapping error bars, statistical difference is unlikely to be present in the sample-to-sample breakdown voltages providing interfacial flashover occurs. Similarly, there is unlikely to be statistical difference between the breakdown voltage of the composite systems using the Nylon 6,6 and PMMA polymers, with the likelihood of statistical similarity also observed between these systems and those utilising the TORLON polymer when interfacial flashover was the breakdown mechanism. Statistical similarity is also likely in the interfacial flashover voltage of three of the five composite samples which employ the DELRIN polymer, however Sample 3 and 4 exhibit a statistically lower breakdown voltage than both the Nylon 6,6 and PMMA composite systems. Interestingly, the highest level of breakdown voltage was seen to occur in the interfacial flashover of Sample 1 of the liquid-PMMA composite systems, above even that of the TORLON samples that experienced bulk breakdown of the polymer. The lowest breakdown voltage observed for any of the synthetic ester-polymer composite insulating systems was that of the third sample of the liquid-DELRIN composite, which as aforementioned is statistically lower than all other synthetic ester-polymer combinations.

Figure 7-3b provides the time to breakdown for each of the synthetic ester-polymer composite samples when stressed with positive lightning impulse voltage. From the figure, it is clear that identical behaviour can be observed as was discussed for the breakdown voltage of the samples. Again, statistical difference is unlikely to be present in the values of time to breakdown for a given liquid-polymer combination providing interfacial flashover occurs. This is also the case when comparing the time to breakdown of all liquid-polymer composite systems that experienced interfacial flashover; which is in slight contrast to the observations made in the breakdown voltage data where two samples of the liquid-DELRIN composite exhibited a statistically lower interfacial flashover voltage than the other composite systems. This can be attributed to the wider spread of the time to breakdown data, resulting in larger error bars for the samples in question. As with the breakdown voltage data, the longest time to breakdown was calculated for the first tested sample of the liquid-PMMA composite; which again surpasses even the samples that experienced bulk breakdown of the polymer. There is again a greater difference between the longest and shortest values of time to breakdown (~43%) as compare with that of the breakdown voltage (~31%); measured for Sample 1 of the liquid-PMMA composite and Sample 4 of the liquid-DELRIN.



(a) (b)

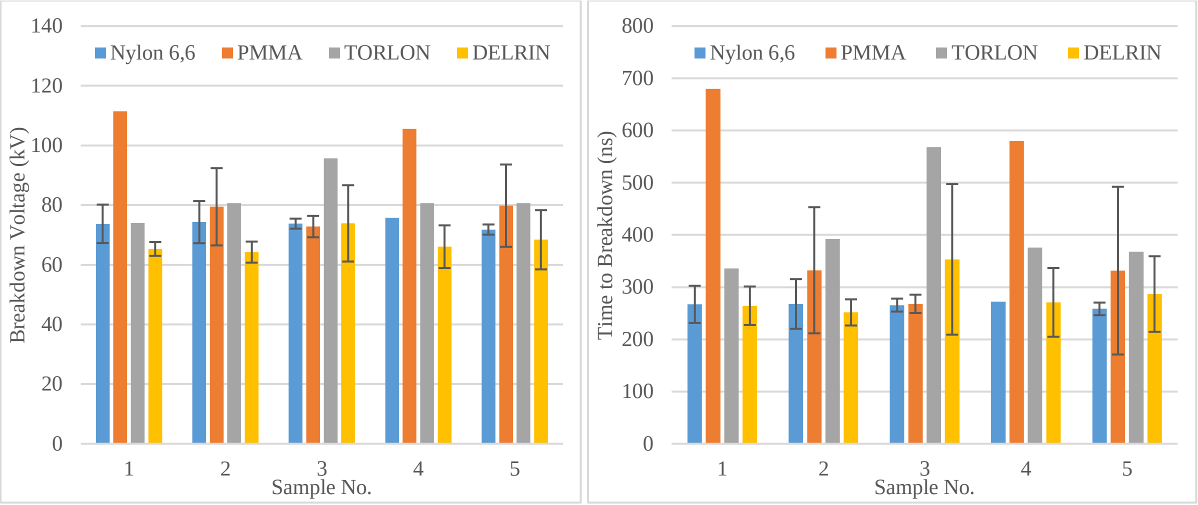
Figure 7-4; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltages obtained for the synthetic ester-polymer composite systems when test samples were stressed with negative lightning impulse are shown in Figure 7-4a. As was the case when the impulse was of positive polarity, composite systems formed of the dielectric liquid and the PMMA polymer favour interfacial flashover, with this observed for all samples tested. The probability of interfacial flashover occurring is seen to reduce for all other synthetic ester-polymer combinations when the impulse is of negative polarity; with the liquid-Nylon 6,6 composite most susceptible to this with the occurrence of interfacial flashover reducing from 100% to 20% of samples when the impulse is of negative polarity as opposed to positive. The highest level of breakdown voltage is still observed for the liquid-PMMA composite systems, providing interfacial flashover occurs. This is unlike what was observed in the positive breakdown voltage data where the liquid-PMMA composite exhibited the highest dielectric strength irrespective of the type of breakdown that occurred. Composite systems that use the Nylon 6,6 polymer are now seen to have the highest breakdown voltage when bulk breakdown of the polymer is observed. Similar to breakdown under positive voltage stress; all composite systems that underwent interfacial flashover exhibit what can be assumed to be a statistically similar level of breakdown voltage.

Figure 7-4b shows the time to breakdown of the synthetic ester-polymer composite systems when stressed with negative lightning impulse voltage. As with the data presented in Figure 7-4a (breakdown voltage), the highest value of time to breakdown was observed for the liquid-Nylon 6,6 composite when bulk breakdown of the polymer occurred (Sample 3). Again, the difference between the longest and shortest time to breakdown is much greater than that which exists between the highest and lowest breakdown voltages. The longest time to breakdown is ~2.5 times that of the shortest, observed for Sample 3 of the Nylon 6,6 and Sample 2 of the TORLON polymers respectively; with the difference in breakdown voltages for these samples only 31%. As both samples experienced bulk breakdown the large difference is attributed to the specific propagation path taken by the breakdown streamer. Further to this the breakdown of the liquid-Nylon 6,6, sample took place at the peak of the applied impulse (nominal rise-time 1200ns), thus, the change in voltage would be minimal as compared with the change in time to breakdown. In all cases bulk breakdown of the polymer requires a longer time to breakdown than when interfacial flashover occurs. Again, there is likely to be no statistical difference in the time to breakdown of any liquid-polymer composite systems when interfacial flashover was observed due to the overlap in the sample error bars.

7.2.3. Breakdown of natural ester-polymer composite insulation

This section of the thesis is dedicated to the presentation of data obtained from experiments involving composite insulating systems consisting of the natural ester (Envirotemp FR3) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) when placed under standard lightning impulse voltage stress. The affect voltage polarity has on breakdown of the composite samples was evaluated with the use of both positive and negative polarity impulse during the experimental study (five samples of each composite system for a given impulse polarity). The breakdown voltage and associated time to breakdown for the composite systems was recorded for the purpose of mean value analysis.



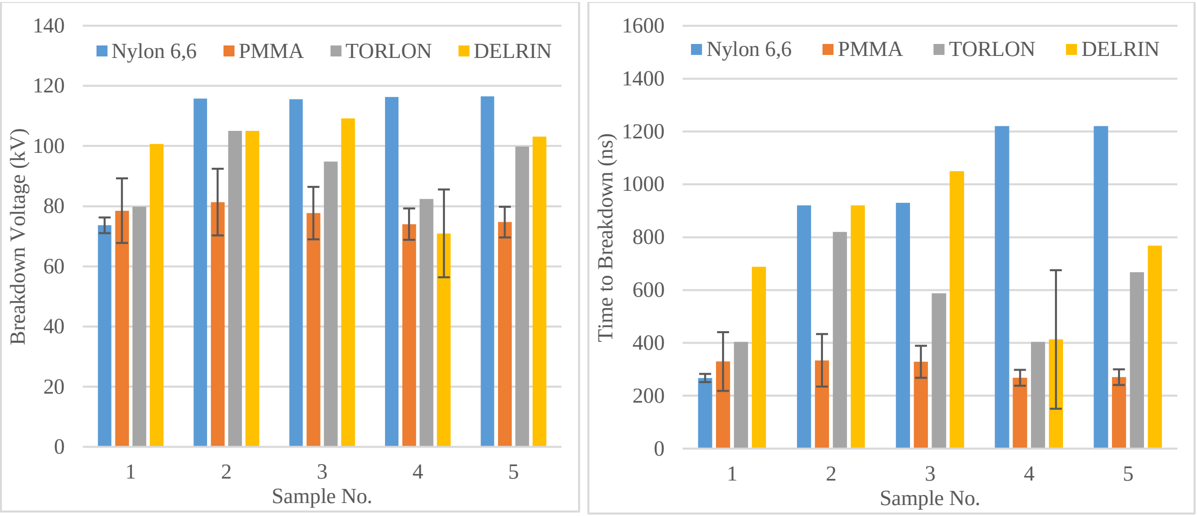
(a)

(b)

Figure 7-5; *Positive lightning impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltage data obtained from the stressing of the natural ester-polymer composite insulating systems with positive lightning impulse is depicted in Figure 7-5a. It is evident that natural ester-polymer composite systems that utilise TORLON favour bulk breakdown of the polymer, with this observed for all samples tested. From the data provided it is clear that the most common type of breakdown experienced by the other three polymers is interfacial flashover, with this occurring in 100% of tests involving the DELRIN polymer, 80% when the Nylon 6,6 was used and 60% of experiments utilising the PMMA. The highest levels of breakdown voltage were measured for composite systems consisting of the dielectric fluid and the PMMA, with this observed for both types of breakdown. Composite systems formed with the TORLON polymer exhibit the lowest breakdown voltage for the systems that experienced bulk breakdown, with liquid-DELRIN systems observed to have the lowest interfacial flashover voltage. That said as all error bars overlap any differences between the interfacial flashover voltages of the natural ester-polymer systems are unlikely to be of statistical significance.

The time to breakdown measured for each of the natural ester-polymer composite samples when under positive lightning impulse voltage can be seen above (Figure 7-5b). Identical behaviour can be observed as was discussed for the breakdown voltage of the samples. Again, statistical difference is unlikely to be present in the values of time to breakdown for a given natural ester-polymer combination providing interfacial flashover occurs. This is also the case when comparing the time to breakdown of the liquid-polymer systems that experienced interfacial flashover in isolation. Interestingly, two samples of the liquid-DELRIN composite (Sample 3 & 4) exhibit a longer time to breakdown than those same samples employing the Nylon 6,6 polymer despite having a lower breakdown voltage. This can be attributed to the wider spread of the time to breakdown data for the liquid-DELRIN samples, which clearly contain outlying values that are affecting the mean time to breakdown; evident in larger error bars for the samples in question. The longest time to breakdown was calculated for the first tested sample of the liquid-PMMA composite for which bulk breakdown of the polymer was observed; this sample also exhibited the highest recorded breakdown voltage of all the natural ester-polymer samples. The longest time to breakdown when interfacial flashover occurs was observed for the third sample of composite systems using the DELRIN polymer, this is in contrast to what was seen in the breakdown voltage data where the liquid-PMMA systems had the highest interfacial flashover strength. As aforementioned this unexpected behaviour of the liquid-DELRIN sample is a consequence of the wide spread of the experimental data measured for this sample. The shortest time to breakdown was observed for the liquid-DELRIN polymer when interfacial flashover occurred, when bulk breakdown was experience it was the liquid-Nylon 6,6 composite system which produced the shortest time to breakdown.



(a) (b)

Figure 7-6; *Negative lightning impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

The negative polarity breakdown voltage of natural ester-polymer composite insulating systems is shown in Figure 7-6a. It is evident that the breakdown behaviour of the natural ester-polymer systems has a sensitivity to the polarity of the energising impulse. The probability of bulk breakdown of the polymer occurring is seen to increase from that observed in the positive polarity tests of the systems utilising the Nylon 6,6 and DELRIN polymers; with likelihood of bulk polymer breakdown increasing by 60% and 80% respectively. Interestingly, under negative lightning impulse voltage the probability of bulk breakdown of the polymer is observed to reduce by 40% from that seen during positive impulse tests for the composite systems employing the PMMA as the polymer dielectric; with all samples now experiencing interfacial flashover. Composite systems formed from the natural ester and the TORLON polymer show no sensitivity to impulse polarity with all samples tested under negative lightning impulse exhibiting identical breakdown behaviour to that observed when the impulse was of positive polarity, with bulk breakdown of the polymer occurring in all tests. When bulk breakdown was observed the composite systems using the Nylon 6,6 polymer demonstrated the highest breakdown strength, while those utilising TORLON consistently have the lowest breakdown strength. When interfacial flashover was the breakdown mechanism composite systems formed with the PMMA polymer always have the highest breakdown voltage, with the lowest voltages measured for systems utilising DELRIN. However, as the error bars for all samples overlap these sample-to-samples differences in interfacial breakdown voltage are unlikely to be statistically significant.

The data relating to the time to breakdown of the natural ester-polymer composite insulation when under negative lightning impulse can be seen in Figure 7-6b. In the most part the data is in good agreement with that of the breakdown voltage, with the liquid-Nylon 6,6 systems shown to require the longest time to breakdown when polymer breakdown occurs and those utilising the TORLON the shortest. However when comparing the time to breakdown of the composite systems that experienced interfacial flashover dissimilarity with breakdown voltage is observed. The longest time to breakdown of composite systems that underwent this type of breakdown does not occur for a liquid-PMMA sample, as would be expected given the findings from analysis of the breakdown voltage data, rather it is the third liquid-DELRIN sample which requires the longest time to breakdown. It is postulated that this is the case because of an outlying data point within the test data which has increased the mean value of time to breakdown significantly; visually confirmed by the large error bars associated with the sample. Given this, the composite systems formed of the natural ester and Nylon 6,6 are now shown to have the shortest time to breakdown when flashover of the liquid-polymer interface occurs, which as aforementioned is contradictory to what was seen in the breakdown voltage data; for the reasons already discussed.

7.2.4. Summary of the lightning impulse breakdown of liquid-polymer composite insulation

The preceding sections of this chapter were dedicated to the presentation and discussion of the lightning impulse breakdown of composite insulating systems formed from the chosen dielectric liquids (mineral oil Shell Diala S4, synthetic ester MIDEL 7131 and natural ester Envirotemp FR3) and four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN). During the experimental work both positive and negative impulses were used in order to ascertain what, if any, affect voltage polarity would exert on breakdown behaviour of the composite insulating systems. Data on the breakdown voltage and time to breakdown was obtained for liquid-polymer systems which experienced ten individual interfacial flashover events or one single bulk breakdown of the polymer dielectric.

Table 7-1; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with positive lightning impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	96.7 ± 5kV	114.6 ± 1.9kV	83.7 ± 14.6kV	88 ± 15.1kV
		473 ± 65ns	1016 ± 142ns	459 ± 203ns	509 ± 242ns
	MIDEL 7131			79.9kV	
				313ns	
	Envirotemp FR3	75.7kV	108.5kV	82.4 ± 8kV	
		272ns	630ns	408 ± 92ns	
Interfacial Flashover	Shell Diala S4				66.6 ± 7.8kV
					289 ± 63ns
	MIDEL 7131	71.2 ± 2.3kV	74.9 ± 6.5kV	64.3 ± 3.4kV	63.5 ± 6.6kV
		251 ± 19ns	275 ± 49ns	267 ± 37ns	247 ± 49ns
	Envirotemp FR3	73.4 ± 4.8kV	77.4 ± 11.2kV		67.6 ± 8.5kV
		265 ± 30ns	311 ± 117ns		285 ± 85ns

Table 7-1 provides the average levels of breakdown voltage and associated time to breakdown calculated for each of the liquid-polymer combinations when stressed with positive lightning impulse. Average values of the breakdown parameters are given ± the standard deviation calculated for the entire dataset of the parameter. The size of the datasets vary based on the number of breakdowns of a particular type experienced by a given liquid-polymer combination. In the case of interfacial flashover the maximum size of the dataset is n = 50 (all samples experienced ten individual flashovers), with the minimum n = 10 (when flashover was observed in the breakdown of a single sample). When the breakdown takes the form of bulk polymer breakdown the largest dataset is n = 5 (all tested samples underwent bulk breakdown of the polymer) with the smallest n = 1 (bulk breakdown occurs for a single sample). Standard deviation has not been calculated for any dataset that contains less than three data points; though mean value calculations were still performed on datasets of such size. Any table entries which contain no data (greyed out) indicate than no breakdowns of that type occurred for the given liquid-polymer combination.

When examining how the liquid-Nylon 6,6 polymer insulating systems perform it is clear that when immersed in the ester fluids this particular composite favours breakdown in the form of interfacial flashover, observed in 100% of tests when the polymer was submerged in synthetic ester and 80% of those in natural ester. A tendency for bulk polymer breakdown is observed when the Nylon 6,6 is immersed in the mineral oil; with this form of breakdown occurring in all tested samples. The interfacial flashover voltage of the ester-Nylon 6,6 composite systems are likely to be statistically similar as are the values of time to breakdown. That said, the highest dielectric strength of the liquid-Nylon 6,6 composites is calculated for insulating systems using the mineral oil as the liquid dielectric when bulk polymer breakdown occured.

Composite systems formed from the ester fluids and the PMMA again show the same tendency for interfacial flashover as was seen with those employing the Nylon 6,6 polymer; with the same probability of interfacial flashover occurring; 100% and 80% when immersed in the synthetic ester and natural ester respectively. Interfacial flashover voltage of the ester-PMMA composite systems is once more likely to be statistically similar. PMMA immersed in mineral oil again exhibits favourability for bulk polymer breakdown with this occurring for all tested samples. The mineral oil-PMMA composite systems are observed to require the highest breakdown voltage and longest time to breakdown of all liquid-PMMA composites insulating systems.

When immersed in the natural ester and mineral oil the TORLON polymer has a 100% probability of experiencing bulk breakdown, with this occurring at what is likely to be a statistically similar level of voltage and time to breakdown for these liquid-polymer systems. Insulating systems utilising the TORLON polymer are the only liquid-polymer composites that experience bulk polymer breakdown when the synthetic ester is used as the dielectric liquid, although this only occurs for a single test sample. Only the synthetic ester-TORLON composite systems are observed to experience interfacial flashover when stressed with positive lightning impulse; occurring in 80% of tests.

DELRIN was the only polymer which experienced interfacial flashover when immersed in mineral oil, however bulk breakdown of this liquid-polymer combination was also observed. Composite insulating systems formed of the mineral oil and DELRIN polymer underwent both bulk breakdown of the polymer (60% of tests) and interfacial flashover (40% of tests). Again, composite systems that utilise the synthetic ester favour interfacial flashover, with this also the case for those utilising the natural ester; with this form of breakdown observed in 100% of tests involving the ester fluids. Interfacial flashover of the liquid-DELRIN composite insulation is seen to occur at a level of voltage and time to breakdown that is likely to be statistically similar for all three liquid-polymer combinations.

Positive breakdown voltage, and time to breakdown, is shown to be higher for composite systems that experience bulk polymer breakdown than those where interfacial flashover took place. Composite systems consisting of the PMMA polymer have the highest breakdown strength when comparing like-for-like breakdown, with systems using the TORLON polymer the lowest. When comparing how the dielectric liquid may affect the breakdown strength of the liquid-polymer composite insulating systems it is evident that when bulk breakdown occurs composite systems formed of the mineral oil and the polymers have a statistically higher breakdown voltage, and longer time to breakdown, than composites using the ester fluids. This is true for all cases but those systems that utilise the TORLON polymer, for which bulk breakdown occurs at a level of voltage that is likely to be statistically similar for all liquid-

TORLON systems. When interfacial flashover occurs all liquid-polymer combinations exhibit a breakdown voltage and time to breakdown that is likely to be absent of statistical difference.

Table 7-2; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with negative lightning impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	113.4 ± 2.3kV	114kV	103.7 ± 4.6kV	106.1 ± 1kV
		950 ± 176ns	1150ns	686 ± 155ns	1040 ± 20ns
	MIDEL 7131	114.1 ± 4.2kV	▨	96.9 ± 7.4kV	99.4 ± 5.3kV
		1019 ± 304ns	▨	666 ± 163ns	700 ± 226ns
	Envirotemp FR3	116 ± 0.4kV	▨	92.4 ± 10.9kV	104.5 ± 3.6kV
		1073 ± 170ns	▨	577 ± 178ns	857 ± 161ns
Interfacial Flashover	Shell Diala S4	71.7 ± 2.6kV	88.4 ± 9.8kV	▨	72.6 ± 13.7kV
		257 ± 15ns	387 ± 208ns	▨	359 ± 185ns
	MIDEL 7131	78.8 ± 1.3kV	83.7 ± 8.1kV	▨	76.1 ± 12.9kV
		365 ± 280ns	334 ± 59ns	▨	359 ± 123ns
	Envirotemp FR3	73.7 ± 2.6kV	77.3 ± 8.6kV	▨	71 ± 14.6kV
		267 ± 16ns	306 ± 78ns	▨	353 ± 262ns

The breakdown parameters obtained when the liquid-polymer composite insulting systems were stressed with negative lightning impulse have been summarised in Table 7-2. The first observation to be made is that all composite systems aside from those employing the TORLON polymer show a sensitivity to impulse polarity which affects the probability of the system experiencing a particular type of breakdown. Furthermore, when the impulse is of negative polarity the breakdown of a given liquid-polymer composite system occurs at a higher, or likely statistically similar, level of voltage and time to breakdown to that under positive impulse, providing a comparable type of breakdown occurs; i.e. interfacial flashover of a given combination occurs under both impulse polarities.

Under negative lightning impulse the composite systems utilising the Nylon 6,6 polymer exhibit behaviour which is dependent on the dielectric fluid used. When the polymer is paired with the ester fluids the probability of bulk breakdown of the polymer is seen to increase from that when the impulse is of positive polarity; likelihood of bulk polymer breakdown is increased by 60% for the natural ester-

Nylon 6,6 composite and 80% for systems composed of the synthetic ester and Nylon 6,6. In contrast to this, composite insulating systems formed of the mineral oil and Nylon 6,6 experience a reduction of 20% in the probability of bulk breakdown of the polymer. This form of breakdown is now the favoured type of breakdown for all liquid-Nylon 6,6 combinations when under negative lightning impulse stress, occurring in 80% of tests irrespective of the dielectric liquid surrounding the polymer. Bulk breakdown of the polymer is observed to take place at a level of voltage that is likely to be of statistical similarity for all liquid-Nylon 6,6 composite systems. When interfacial flashover occurs composite systems formed from the polymer and the synthetic ester are seen to exhibit the highest breakdown voltage of systems experiencing this type of breakdown; statistically higher than those using both the mineral oil and natural ester, which both demonstrate a likelihood of statistical similarity in the voltage necessary to cause breakdown of the insulating system.

For composite systems formed of the PMMA polymer and the mineral oil or natural ester the probability of bulk breakdown of the polymer is also seen to reduce when the impulse is of negative polarity; again no observation of bulk polymer breakdown was made for the synthetic ester-PMMA systems. Probability of polymer breakdown is reduced by 40% for the natural ester-PMMA systems, with the likelihood of this form of breakdown seen to decrease by 80% for composite systems formed with the PMMA and mineral oil. Under negative lightning impulse stress the favoured type of breakdown for the liquid-PMMA composite systems is interfacial flashover; with this observed in 100% of tests involving the ester fluids and 80% when the polymer was immersed in mineral oil. All liquid-PMMA combinations exhibit a breakdown voltage and time to breakdown that can be assumed likely to be statistically similar when interfacial flashover took place.

Under negative lightning impulse liquid-TORLON, insulating systems were the only composites of those investigated to universally experience bulk breakdown of the polymer; with this occurring in all tests irrespective of the dielectric liquid used. Demonstrating that when under negative impulse the probability of bulk breakdown of the polymer is increased as compared with when the composite systems were stressed with positive impulse. The probability of this type of breakdown occurring for the synthetic ester-TORLON systems is observed to increase by 80%, to 100% of tests, while the probability for the natural ester and mineral oil-based systems remains unchanged at 100%. Breakdown of the liquid-TORLON composite systems (bulk polymer breakdown) takes place at a level of voltage and time to breakdown that is likely to be statistically similar for all liquid-TORLON combinations when under negative lightning impulse voltage.

When stressed with negative polarity lightning impulse the probability of liquid-DELRIN composite insulation suffering bulk breakdown of the polymer increases for liquid-polymer combinations that utilise the ester fluids as compare with that seen under positive voltage stress. Synthetic ester-DELRIN systems now show a 40% probability of experiencing bulk polymer breakdown, with systems that use the natural ester exhibiting an 80% probability of such breakdown occurring; this represents a 40% and 80% increase respectively, with neither liquid-DELRIN combination experiencing bulk breakdown of the polymer when the impulse was of positive polarity. The probability of bulk polymer breakdown for the mineral oil-DELRIN composite systems remains unchanged from that observed during testing under positive voltage stress (60%). When bulk polymer breakdown is observed the breakdown voltage and time to breakdown of mineral oil-DELRIN and natural ester-DELRIN systems are shown to have a likely absence of statistical difference. While the breakdown parameters of the synthetic ester-based systems are likely to be statistically similar to that of composites utilising the natural ester they are statistically lower than those of the systems using the mineral oil. When breakdown takes the form of interfacial flashover all liquid-DELRIN composite systems exhibit a probable absence of statistical difference in breakdown voltage and time to breakdown.

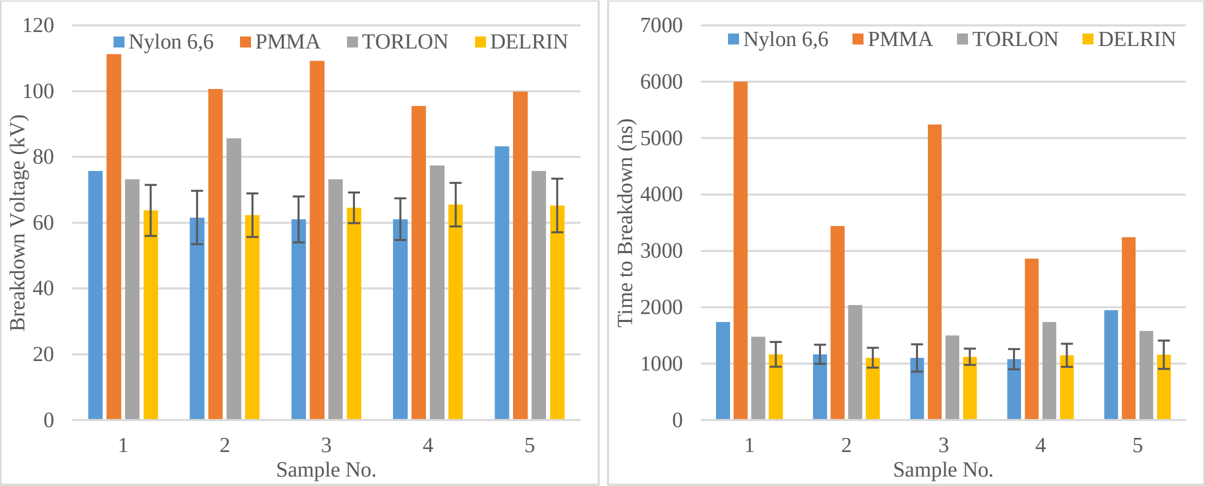
7.3. Breakdown of liquid-solid composite insulation under 7μs impulse

The following sections present results obtained from experimental work conducted to ascertain the breakdown characteristics of liquid-polymer composite insulating systems when stressed with impulses longer than the standard lightning impulse. During these experiments liquid-polymer composites formed from mineral oil (Shell Diala S4), synthetic ester (MIDEL 7131), natural ester (Envirotemp FR3) and practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with the same microsecond impulse (rise-time of 7μs) as was used in the work discussed in Chapter 5 of this thesis.

As aforementioned (Section 7.2), the liquids used in this work were in the 'As Received' state, meaning that tests were conducted with liquids in same condition as supplied by the manufacturer. Data on breakdown voltage and associated time to breakdown was obtained from both flashover of the liquid-polymer interface as well as bulk breakdown of the polymer for the purpose of mean value analysis.

7.3.1. Breakdown of mineral oil-polymer composite insulation

Composite insulating systems formed of the mineral oil (Shell Diala S4) and the four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with microsecond impulse voltage. Experiments were conducted to the same methodology described in Section 3.6.2, with ten samples of each liquid-polymer combination used within the experimental work. Five samples were stressed with positive polarity microsecond impulse, while the remaining five samples were exposed to an identical impulse of negative polarity. The breakdown voltage and time to breakdown of each liquid-polymer sample was analysed for mean values (when ten flashovers of the interface occurred) or simply stated if bulk breakdown of the polymer occurred.

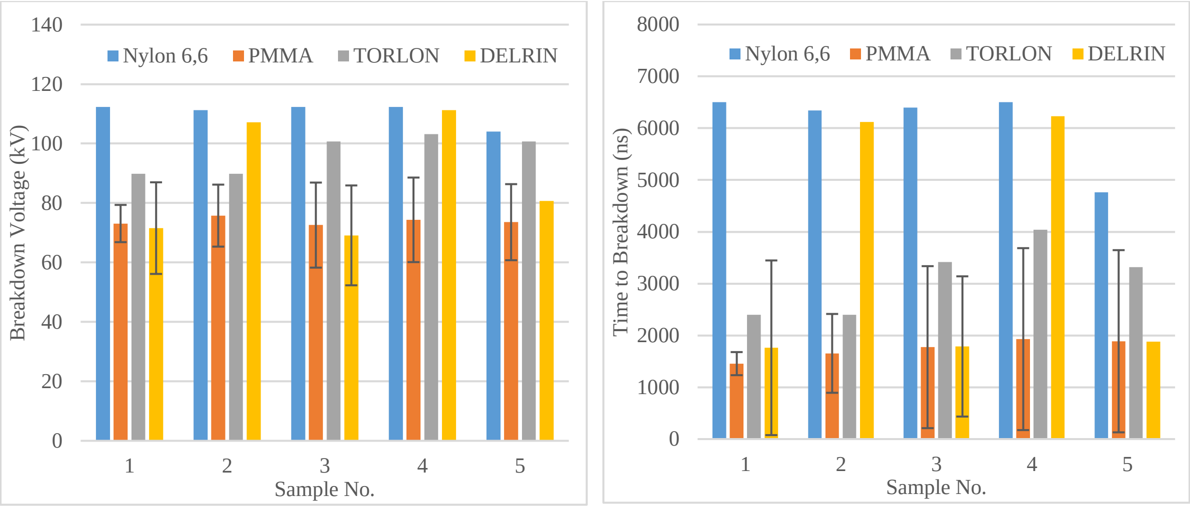


(a) (b)

Figure 7-7; *Positive 7μs impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltage of each of the mineral oil-polymer composite insulating systems when under positive microsecond impulse can be seen in Figure 7-7a. Experimental data has been presented for both interfacial flashover and bulk breakdown of the polymer dielectric. Data devoid of error bars represents an insulation system that experienced bulk polymer breakdown, with all other data showing samples which underwent ten individual interfacial flashover events. The errors bars associated with the data represent the standard deviation in the breakdown voltage of the ten observed interfacial flashover events. From Figure 7-7a it is evident that breakdown of the polymer dielectric consistently occurs at a higher voltage level than that of the surface flashover of the liquid-polymer interface. Bulk breakdown of the insulating systems which utilise the PMMA polymer have the highest dielectric strength and clearly demonstrate a favourability for bulk breakdown of the polymer with this observed in 100% of tests. Bulk polymer breakdown was also seen to occur universally for composite systems formed from the TORLON polymer, though at a lower level of voltage than those utilising the PMMA polymer. Composite systems using the Nylon 6,6 polymer also exhibit some cases of bulk polymer breakdown, although this is not the predominate type of breakdown experienced by this liquid-polymer composite, only occurring in 40% of tests. Only two of the four mineral oil-polymer systems investigated experience interfacial flashover; those utilising the Nylon 6,6 and DELRIN polymers. It can be seen in the presented data that mineral oil-DELRIN composite insulation favours interfacial flashover under positive microsecond impulse voltage, with this observed in all tests of this system. As aforementioned the Nylon 6,6 polymer also shows a tendency for interfacial flashover, though at a lower probability than the systems using the DELRIN polymer; 60% of tests as compared with 100% for the DELRIN polymer. Flashover of the mineral oil-DELRIN and mineral oil-Nylon 6,6 interfaces occur at a level of voltage that is likely to be statistically similar for all samples. When comparing the interfacial flashover voltage of the mineral oil-Nylon 6,6 composite to that of bulk breakdown of the polymer it is clear that interfacial flashover occurs at a significantly lower level of voltage, as much as 27% below that of polymer breakdown voltage.

The time to breakdown of the mineral oil-polymer composite systems is shown in Figure 7-7b. The measured data is in good agreement with that of the breakdown voltage with mineral oil-PMMA systems exhibiting the longest time to breakdown. When comparing these systems to the others which experienced bulk breakdown of the polymer is can be seen that PMMA systems have a significantly longer time to breakdown than the other mineral oil-polymer combinations for which bulk breakdown was observed; more than 4 times that of TORLON polymer and 3.4 times greater than systems formed with the Nylon 6,6 polymer. This difference between values of time to breakdown is much larger than was observed in the breakdown voltage of the corresponding liquid-polymer samples. This is a consequence of the breakdown of the PMMA-based systems taking place near the peak of the voltage impulse where the change in voltage is minimal as compared with the change in the time to breakdown. As with the breakdown voltage data, there is likely to be no statistical difference in the time to breakdown of the mineral oil-polymer insulating systems, given the overlapping error bars, when interfacial flashover is observed.



(a) (b)

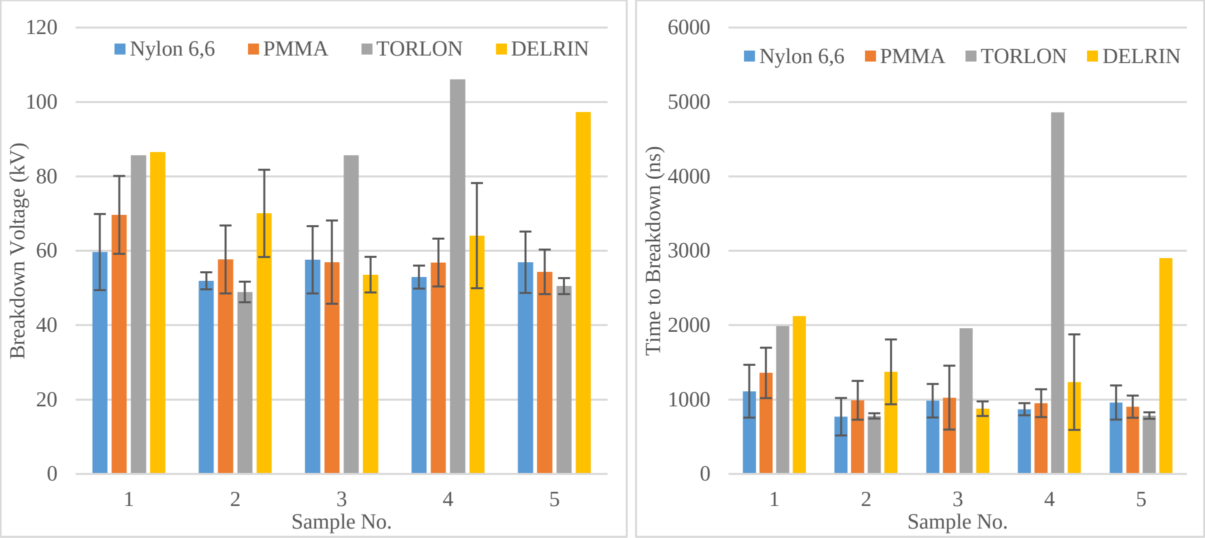
Figure 7-8; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

When examining the breakdown voltage of the mineral oil-polymer composite insulating systems when stressed with negative microsecond impulse (Figure 7-8a) it is clear that all mineral oil-polymer combinations, expect those using the TORLON polymer, exhibit differing breakdown behaviour to that reported when the impulse was of positive polarity. Composite systems utilising the Nylon 6,6 polymer now favour bulk breakdown of the polymer, with this observed in all tests. This is also the case for the mineral oil-DELRIN systems which also now favour bulk breakdown of the polymer under negative microsecond voltage stress. Unlike during positive voltage tests where only interfacial flashover was observed for the DELRIN systems, the probability of bulk polymer breakdown occurring is now 60%. As aforementioned the breakdown of the mineral oil-TORLON composite is the only insulating system which is unaffected by the change in impulse polarity; again showing a 100% probability of bulk breakdown of the polymer. The highest breakdown voltage is observed for the bulk breakdown of the Nylon 6,6-based systems; although the bulk breakdown of the mineral oil-DELRIN systems are only ~1% lower when comparing the highest breakdown voltages for a given sample. As with positive polarity breakdown the liquid-TORLON composite offers the lowest dielectric strength when like-for-like breakdowns are compared; 20% below the Nylon 6,6 and DELRIN systems providing bulk breakdown of the polymer occurs. The only mineral oil-polymer composite that shows an increase in the probability of interfacial flashover taking place is the PMMA-based composite. While under positive voltage only bulk breakdown of this composite systems was observed, when the impulse is of negative polarity the inverse is true, with only interfacial flashover taking place. Again, there is likely to be an absence of statistical difference in the breakdown voltage of the mineral oil-polymer composite systems that experienced interfacial flashover.

The time to breakdown measured when the mineral oil-polymer composite insulation was placed under negative microsecond impulse voltage shows the same trends as were apparent in the breakdown voltage data. Composite systems formed of the mineral oil and Nylon 6,6 polymer exhibit the longest time to breakdown, when bulk breakdown of the polymer occurs. As with breakdown voltage, the mineral oil-DELRIN systems require a similar time to breakdown to that of the systems using the Nylon 6,6 polymer, providing the breakdown takes the form of bulk polymer breakdown. Interestingly even though Sample 5 of the mineral oil-DELRIN composite underwent bulk breakdown of the polymer it exhibits a time to breakdown close to that of the samples that experienced interfacial flashover. Composite systems that utilise the TORLON polymer are observed to consistently breakdown after the shortest delay time of all the mineral oil-polymer combinations for which bulk breakdown occurred. When breakdown takes the form of flashover of the liquid-polymer interface, as is the case with 100% of the liquid-PMMA samples and 40% of those using the DELRIN polymer, statistical difference is unlikely to exist between the measured values of time to breakdown.

7.3.2. Breakdown of synthetic ester-polymer composite insulation

This section will present experimental data obtained from stressing composite insulating systems formed of the synthetic ester (MIDEL 7131) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) with microsecond impulse voltage. As with the work discussed in the previous sections the influence of voltage polarity on breakdown was evaluated by exposing the liquid-polymer samples to impulses of positive and negative polarity. During testing five samples of a particular composite system were used for a given impulse polarity. Data obtained on the breakdown voltage and associated time to breakdown for the composite systems was then used in mean value analysis.



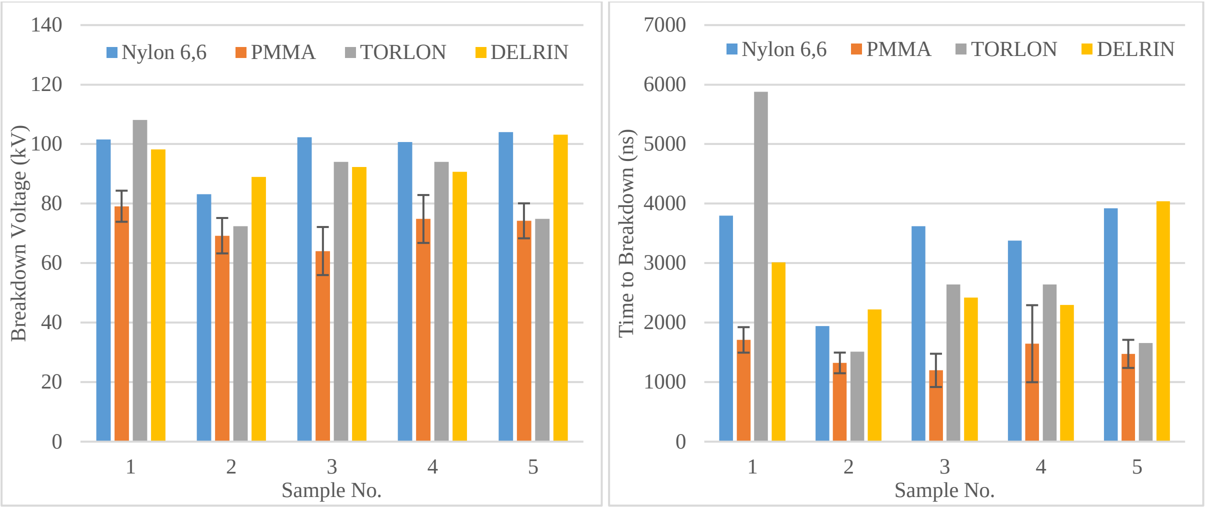
(a) (b)

Figure 7-9; *Positive 7µs impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.*

When examining the positive polarity breakdown voltage of the synthetic ester-polymer composite insulation when stressed with microsecond impulse (Figure 7-9a) it is clear that the TORLON-based systems favour bulk breakdown of the polymer; with this observed in 60% of tests. All other synthetic ester-polymer composites are seen to favour interfacial flashover, with this observed in 100% of tests involving the PMMA and Nylon 6,6-based systems and 60% of those utilising the DELRIN polymer. The highest level of breakdown voltage seen during testing of the synthetic ester-polymer composite insulation was that of the systems using the TORLON polymer when bulk breakdown occurred.

Dielectric strength of this composite was as much as 23% higher than the liquid-DELRIN composite when both systems experienced bulk breakdown of the polymer. Of the synthetic ester-polymer composites that experienced interfacial flashover those formed of the DELRIN polymer offered the highest dielectric strength, while systems using the TORLON demonstrated the lowest breakdown voltage. Interestingly this is in direct contrast to what is observed when bulk breakdown of the polymer occurs. That said any differences that exist between the interfacial flashover voltages of the synthetic ester-polymer composites are unlikely to be significant given the probable statistical similarity in the measured values of breakdown voltage.

The time to breakdown data shows identical trends to those discussed for the breakdown voltage data. The composite systems formed from the synthetic ester and TORLON polymer that experienced bulk breakdown return the longest values of time to breakdown. When comparing these values to those obtained for the DELRIN systems that underwent bulk breakdown of the polymer the TORLON systems requires as much as 2.3 times longer to breakdown when the extreme cases (Sample 3 of TORLON and Sample 1 of the DELRIN system) are evaluated. This is a considerable larger difference than is present in the breakdown voltages of the samples, this discrepancy can be attributed to the shape of the voltage impulse and the specific point on the impulse at which breakdown takes place. As breakdown of the aforementioned TORLON sample takes place at a point at which the change in voltage has slowed, i.e. the gradient of the impulse line is lower, it is to be expected that the difference in time to breakdown would be larger than that present in the breakdown voltage. When the synthetic ester-polymer composite insulating systems that experienced interfacial flashover are compared, again the DELRIN-based system exhibits the longest time to breakdown and the system using the TORLON polymer the shortest, this agrees with the observations made in the breakdown voltage data. However as previously mentioned the likely statistical similarity between samples means that any differences present in the time to breakdown of specific composites may not be significant.



(a) (b)

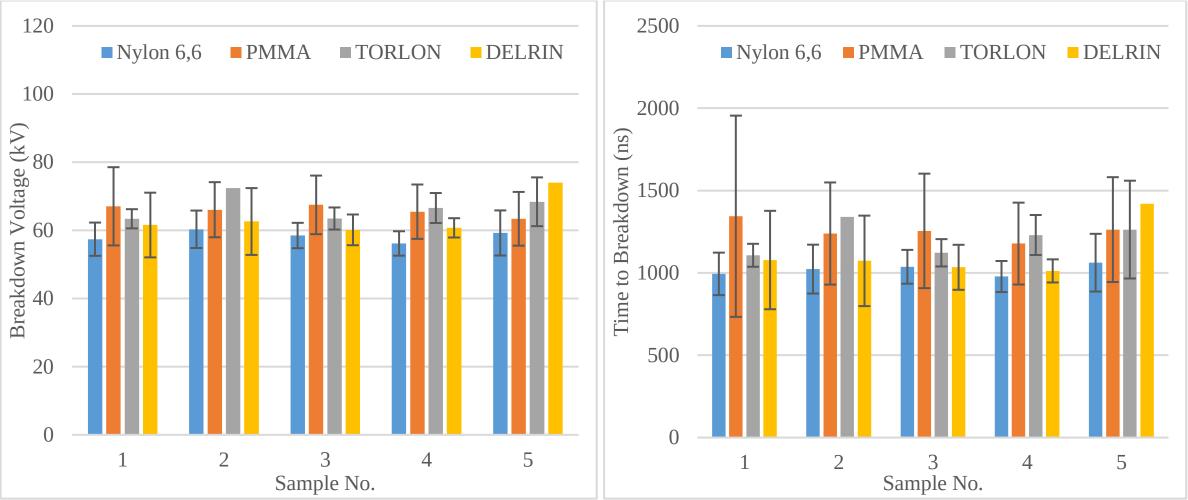
Figure 7-10; *Negative 7μs impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.*

When the breakdown voltage of the synthetic ester-polymer composite insulating systems is evaluated under negative microsecond impulse it is clear that three of the four liquid-polymer systems demonstrate varying breakdown behaviour from that observed under positive impulse stress. While the breakdown of the PMMA-based systems remains unchanged, with all test samples experiencing interfacial flashover, the probability of this form of breakdown occurring for all other synthetic ester-polymer combinations is seen to reduce. Bulk breakdown of the polymer dielectric is now the predominate form of breakdown experienced by all other synthetic ester-polymer systems under negative microsecond impulse, with this seen in 100% of tests involving all other polymers. This represents a complete change in the behaviour of the Nylon 6,6 systems, which experienced no instances of bulk breakdown of the polymer under positive impulse, and an increase of 40% in the probability of this form of breakdown occurring for the TORLON and DELRIN systems. As was the case with positive polarity breakdown of the composite systems, the TORLON-based composite exhibits the highest dielectric strength when bulk breakdown of the polymer is observed. Interestingly, this liquid-polymer system also has the lowest recorded breakdown strength for a single sample (Sample 2) when bulk breakdown takes place. As aforementioned, the synthetic ester-PMMA systems are the only composite system to experience interfacial flashover, with all samples exhibiting a likely absence of statistical difference in dielectric strength.

As with breakdown of the composite systems under positive microsecond impulse, the time to breakdown measured for each of the synthetic ester-polymer combinations agrees well with that of the breakdown voltage. When breakdown takes the form of bulk polymer breakdown the liquid-TORLON systems show the longest time to breakdown (Sample 1) as well as the shortest (Sample 2). This highlights the large variability in the breakdown behaviour of this particular composite system; with the longest time to breakdown for this combination nearly 4 times that of the shortest. Again, this is a significantly larger difference than exists between the breakdown voltages of these samples, once more attributed to the point on the energising impulse at which breakdown of the sample takes place. Composite systems formed of the synthetic ester and PMMA, the only insulating systems to experience interfacial flashover under negative impulse, again show the likely absence of statistical difference in the time to breakdown of all samples.

7.3.3. Breakdown of natural ester-polymer composite insulation

Within this section data obtained when stressing the composite insulating systems consisting of the natural ester (Envirotemp FR3) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) with microsecond impulse will be presented. The influence of voltage polarity on the breakdown characteristics of the liquid-polymer composites was evaluated by applying both positive and negative polarity impulse during the experimental study. Five samples of each composite system were exposed to a given impulse polarity. Experimental data on the breakdown voltage and associated time to breakdown of the composite systems was logged for the purpose of mean value analysis.

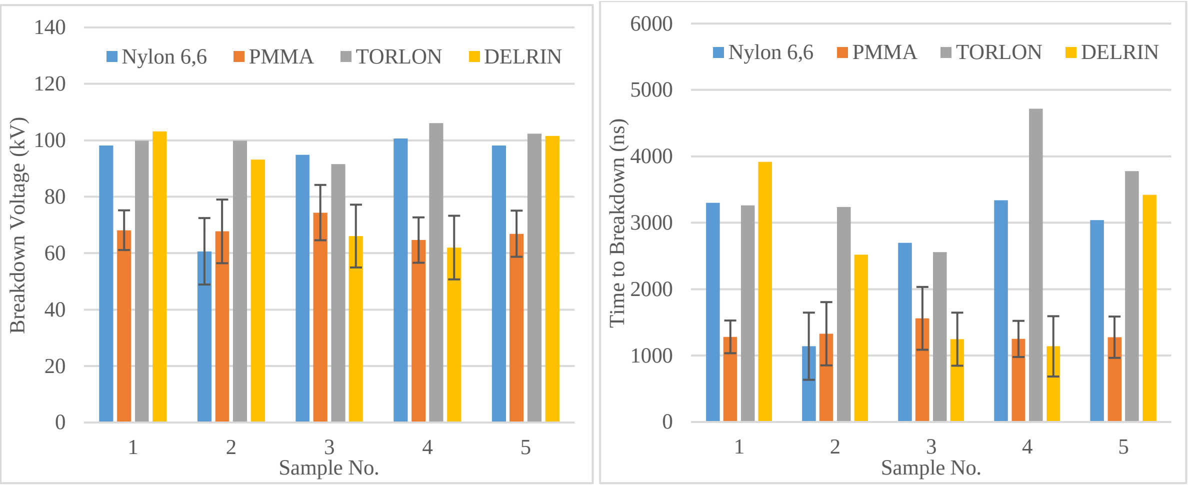


(a) (b)

Figure 7-11; *Positive 7μs impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltages obtained for each of the natural ester-polymer composite systems when under positive microsecond impulse are shown above (Figure 7-11a). From the data shown in the figure it is clear that all natural ester-polymer composite systems favour breakdown in the form interfacial flashover; with this observed in 100% of tests involving systems utilising the Nylon 6,6 and PMMA polymers and 80% of those using the TORLON and DELRIN polymers. When bulk breakdown of the polymer is observed the DELRIN-based systems exhibit the highest breakdown voltage and those utilising the TORLON polymer the lowest. Though as can be seen from the data presented in Figure 7-11a the bulk breakdown voltage of the aforementioned polymers is very close to that of the highest interfacial flashover voltage, observed for Sample 1 of the PMMA-based composite; with only a 10% difference between these values. When evaluating the interfacial flashover of the systems it can be seen that all natural ester-polymer composites exhibit a level of breakdown voltage that is likely statistically similar to one another.

Figure 7-11b depicts the time to breakdown of the four synthetic ester-polymer combinations. Analysis of this data shows that both breakdown parameters (breakdown voltage and time to breakdown) have identical tendencies. Composite systems that experience bulk breakdown of the polymer require the longest time to breakdown; with the DELRIN system taking longer to breakdown than the TORLON-based composite. Similar to what was observed in the breakdown voltage data, the bulk breakdown of the DELRIN composite and the interfacial flashover of the PMMA composite exhibit comparable delay times; with the time to breakdown of the DELRIN composite only 6% longer than that of the PMMA system. This is a small difference than was reported in the breakdown voltages of these systems, which can be attributed to individual data within the dataset of the PMMA sample increasing the mean time to breakdown; this can be seen in the large error bar associated with this composite sample. This wide spread of the PMMA sample data has also resulted in the mean time to breakdown of this sample being greater than that of the TORLON sample that experienced bulk breakdown (Sample 2). When examining the composite systems for which interfacial flashover occurred it is clear that the error bars for all systems overlap and thus statistical similarity can be assumed in the time to breakdown; as was the case with the breakdown voltage of these systems.



(a)

(b)

Figure 7-12; *Negative 7µs impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

From examination of the negative polarity breakdown voltages of the natural ester-polymer composites it is evident that breakdown behaviour differs from that observed under positive impulse stress for all but the PMMA-based systems. Bulk breakdown of the polymer is now the predominate form of breakdown experienced by all but the PMMA composite systems, which again favour interfacial flashover. Under negative energisation composite systems utilising the Nylon 6,6 and TORLON polymers experience an 80% increase in the probability of bulk breakdown of the polymer occurring, while for those consisting of the DELRIN polymer a 40% increase is observed. Similar to when the impulse was of positive polarity, the highest breakdown voltage is seen for the TORLON composite when bulk breakdown of the polymer occurs; with this now much greater than for the composite systems which experienced interfacial flashover. Again, all systems experiencing interfacial flashover have a likely absence of statistical difference in their breakdown voltages.

The values of time to breakdown once again agree well with that of the sample breakdown voltages. When bulk breakdown of the polymer was observed it is the systems formed with the TORLON polymer that exhibit the longest time to breakdown; though with the greatest variability between highest and lowest values. Composite systems formed of the natural ester and the Nylon 6,6 polymer exhibit the smallest variation in longest and shortest values of time to breakdown, providing bulk breakdown was observed. The shortest value of time to breakdown for a composite system that experienced bulk breakdown of the polymer was that of the DELRIN-based system; 53% lower than that of the longest recorded time to breakdown; observed for the TORLON system. Once more, when breakdown takes the form of interfacial flashover there is unlikely to be a statistical difference in the measured values of time to breakdown for any composite systems.

7.3.4. Summary of the 7μs impulse breakdown of liquid-polymer composite insulation

The previous sections (7.3.1 to 7.3.3) were used to present and discuss the breakdown of composite insulating systems formed from mineral oil Shell Diala S4, synthetic ester MIDEL 7131 and natural ester Envirotemp FR3) and four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) when stressed with 7μs impulse voltage. The experimental work discussed involved stressing the composite insulating systems with impulses of both positive and negative polarity in order to determine the influence voltage polarity may have on the observed breakdown behaviour. The breakdown voltage and time to breakdown was obtained for liquid-polymer systems that experienced either ten individual interfacial flashover events or one single bulk breakdown of the polymer dielectric.

Table 7-3; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with positive 7µs impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	79.5kV	103.5 ± 6.4kV	77.1 ± 5.2kV	
		1845ns	4156 ± 1379ns	1668 ± 232ns	
	MIDEL 7131			92.5 ± 11.8kV	91.9kV
				2937 ± 1666ns	2510ns
	Envirotemp FR3			72.4kV	74.1kV
				1440ns	1420ns
Interfacial Flashover	Shell Diala S4	61.2 ± 6.9kV			64.3 ± 6.7kV
		1115 ± 228ns			1140 ± 195ns
	MIDEL 7131	55.8 ± 7.6kV	59.1 ± 10.1kV	49.7 ± 2.6kV	61.5 ± 12.5kV
		939 ± 262ns	1046 ± 323ns	783 ± 39ns	1131 ± 480ns
	Envirotemp FR3	58.3 ± 5kV	66.3 ± 8.6kV	65.5 ± 5kV	61.3 ± 7.1kV
		1019 ± 131ns	1256 ± 376ns	1181 ± 176ns	1049 ± 210ns

The average levels of breakdown voltage and associated time to breakdown calculated for each of the liquid-polymer combinations when stressed with positive microsecond impulse are shown in Table 7-3. Average values are given ± the standard deviation calculated for the entire dataset of the specific breakdown parameter. The size of a given dataset will depend on the number of breakdowns of a particular type observed for a particular liquid-polymer composite. For interfacial flashover the largest possible dataset is n = 50 (ten individual flashovers observed for all test samples), the smallest will therefore be n = 10 (when a single test sample underwent ten interfacial flashovers). In the case of breakdown taking the form of bulk breakdown of the polymer the maximum dataset is n = 5 (bulk breakdown of the polymer in all tests) with the minimum n = 1 (bulk breakdown occurs for a single sample). Standard deviation was not calculated for any dataset containing less than three data points; however mean value calculations were still performed on datasets of such size. Table entries absent of data (greyed out) show that no breakdowns of that type occurred for the given liquid-polymer system.

When reviewing the data obtained for the breakdown of the composite insulating systems formed of the Nylon 6,6 and the varying dielectric fluids under positive microsecond impulse it is clear that all liquid-Nylon 6,6 composites favour breakdown in the form of interfacial flashover. This type of breakdown was observed universally for composite systems that used the synthetic ester and natural ester fluids as well as in 80% of test for which the mineral oil was the chosen dielectric fluid; with bulk breakdown of the Nylon 6,6 polymer occurring the in remaining 20%. The highest recorded breakdown voltage, and longest time to breakdown, was observed in the test in which the mineral oil-Nylon 6,6 composite underwent bulk breakdown of the polymer. Interfacial flashover voltage can be assumed, given the overlap in the error bars, to likely be statistically similar for all liquid-Nylon 6,6 composite insulating systems.

Composite insulating systems consisting of the PMMA polymer are also seen to favour interfacial flashover providing the ester fluids are the dielectric fluid used within the system. As with the Nylon 6,6-based systems, interfacial flashover is observed in all tests involving of both the synthetic ester-PMMA and natural ester-PMMA insulating systems. Contrastingly, when mineral oil was used as the liquid dielectric for the PMMA-based composite bulk polymer breakdown occurs in 100% of test samples. Bulk breakdown of the polymer is once again seen to occur at a higher level of voltage than that of breakdown in the form of interfacial flashover; though direct comparison cannot be made for a given dielectric liquid. Interfacial flashover voltage, as well as the associated time to breakdown, of the ester-PMMA composites under positive microsecond impulse, as can be seen in Table 7-3, is likely to be statistically similar.

The TORLON-based composite insulation is the only liquid-polymer combination that exhibits bulk breakdown irrespective of the dielectric fluid the polymer is immersed in; with this occurring for 100% of tests conducted with the mineral oil, 60% of those involving the synthetic ester and 20% when the natural ester was used. This demonstrates that under positive microsecond impulse composite systems formed of TORLON and either the mineral oil or the synthetic ester favour bulk breakdown of the polymer, while those utilising the natural ester show a tendency for the occurrence of interfacial flashover. When comparing the composite insulating systems that experienced bulk breakdown it can be seen that the synthetic ester-TORLON systems required a statistically higher breakdown voltage than those utilising the mineral oil; with direct comparison to systems using the natural ester not possible given the single occurrence of this form of breakdown for that particular liquid-TORLON combination.

Interestingly, when interfacial flashover is observed it is systems formed of the polymer and natural ester fluid that offer the best dielectric performance; with breakdown voltage statistically higher than that of the systems utilising the synthetic ester fluid.

Insulating systems consisting of the DELRIN polymer are the only mineral oil-polymer system to have no instances of bulk breakdown of the polymer under positive microsecond impulse. The probability of this form of breakdown taking place is also low for the composite systems using the ester fluids; occurring in 40% of tests conducted with the synthetic ester and only 20% of those involving the natural ester liquid, with breakdown voltage of the former ~50% higher than that of the latter. Data presented in Table 7-3 clearly demonstrates that under positive microsecond impulse all liquid-DELRIN composites favour breakdown in the form of interfacial flashover, with those using the mineral oil offering the highest breakdown strength. However, given the standard deviation in the breakdown parameters (breakdown voltage and time to breakdown) of each liquid-DELRIN combination it can be said that all systems likely perform with statistical similarity.

From the data shown in Table 7-3 it is evident that when stressed with positive microsecond impulse voltage composite systems formed of the mineral oil and PMMA polymer offer the highest breakdown strength, while also having the greatest probability of experiencing bulk breakdown of the polymer. TORLON-based composite systems exhibit the lowest breakdown strength when immersed in synthetic ester if breakdown takes the form of interfacial flashover; however when bulk breakdown is observed, these systems demonstrate a performance that is likely statistically similar to that of mineral oil-PMMA systems. The lowest breakdown strength when the liquid-polymer composites systems experience bulk breakdown is that of the natural ester-TROLON systems. When interfacial flashover is observed statistical similarity in the breakdown parameters of all liquid-polymer combinations is likely given the overlap in the associated error bars.

Table 7-4; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with negative 7µs impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	110.5 ± 3.6kV		96.9 ± 6.5kV	99.7 ± 16.6kV
		6100 ± 752ns		3116 ± 709ns	4743 ± 2480ns
	MIDEL 7131	98.3 ± 8.6kV		88.7 ± 14.9kV	94.7 ± 5.9kV
		3332 ± 804ns		2866 ± 1766ns	2798 ± 760ns
	Envirotemp FR3	97.9 ± 2.4kV		99.9 ± 5.4kV	99.3 ± 5.4kV
		3095 ± 295ns		3512 ± 802ns	3287± 710ns
Interfacial Flashover	Shell Diala S4		73.9 ± 11.5kV		70.8 ± 15.7kV
			1740 ± 1315ns		1690 ± 1497ns
	MIDEL 7131		72.3 ± 8.3kV		
			1470 ± 391ns		
	Envirotemp FR3	60.7 ± 11.8kV	68.4 ± 9.2kV		64 ± 11.1kV
		1141 ± 506ns	1340 ± 372ns		1193 ± 420ns

It is clear from the data shown in Table 7-4 that the breakdown of all liquid-polymer composite systems show a sensitivity to the polarity of the energising impulse. For composites consisting of the Nylon 6,6, PMMA, TORLON and DELRIN polymers the probability of bulk breakdown occurring is observed to increase, as compared with that under positive impulse, when the polymers are immersed in either the synthetic ester or natural ester fluids. This is also the case for the Nylon 6,6 and DELRIN polymers when paired with the mineral oil. The only composite system that experienced a reduced probability of bulk breakdown of the polymer under negative impulse is that formed of the PMMA and mineral oil. From Table 7-4 it is also evident that under negative energisation the breakdown of a given liquid-polymer composite system occurs at a higher, or likely statistically similar, level of voltage and time to breakdown to that when the composite was stressed with positive impulse, providing a comparable type of breakdown occurs.

When stressed with negative polarity microsecond impulse the liquid-Nylon 6,6 composite insulating systems clearly favour bulk breakdown of the polymer; occurring in 100% of test involving the mineral oil and synthetic ester as well as 80% in which the natural ester was used. This represents a complete reversal of the behaviour observed for the synthetic ester-Nylon 6,6 composite under positive voltage stress and an increase of 80% in the probability of this form of breakdown taking place for both the mineral oil and natural ester-based systems. All liquid-polymer combinations exhibit a similar dielectric performance, with a likely absence of statistical difference in breakdown voltage and time to breakdown, when bulk breakdown of the polymer takes place. The only liquid-Nylon 6,6 composite for which interfacial flashover was observed under negative voltage stress was the composite utilising the natural ester. While the types of breakdown cannot be directly compared for the systems using the mineral oil and synthetic ester, it is clear from the data obtained for the natural ester-based systems that a higher level of breakdown voltage is observed for composites that experience bulk breakdown as opposed to that of interfacial flashover.

Composite systems using the PMMA polymer exhibit a clear tendency for breakdown in the form of interfacial flashover; with this observed in 100% of tests irrespective of the dielectric liquid used. This is identical behaviour to that observed under positive impulse for composite systems using the ester fluids but contrasting behaviour for mineral oil-PMMA systems, for which only bulk breakdown of the polymer occurred under positive voltage stress. Under negative microsecond impulse the interfacial flashover voltage, as well as the associated time to breakdown, shows a likely lack of statistical difference for all liquid-PMMA composite insulating systems.

When stressed with microsecond impulse of negative polarity all liquid-TORLON composite insulating systems demonstrate a favourability to experience bulk breakdown of the polymer; occurring in 100% of tests irrespective of the dielectric fluid used in the insulating system. The probability of the liquid-TORLON composite systems utilising the synthetic ester and natural ester to experience bulk breakdown of the polymer is seen to increase by 40% and 80% respectively, while for those using mineral oil probability remains unchanged. All liquid-TORLON composite systems exhibit a comparable dielectric performance with statistical difference in the obtained levels breakdown voltage and time to breakdown unlikely given the overlapping of the associated error bars.

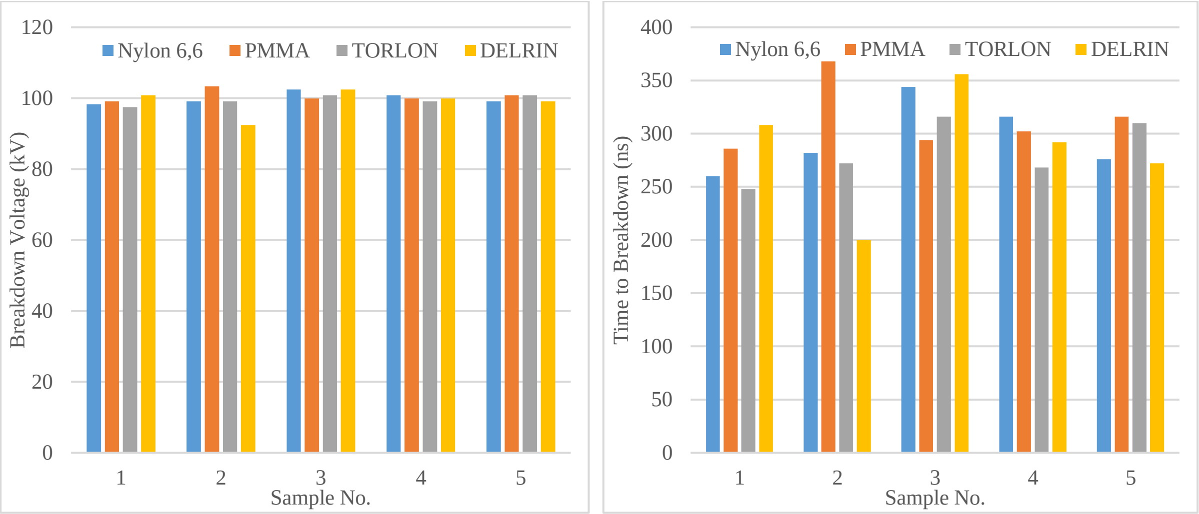
The probability of liquid-DELRIN composite insulation suffering bulk breakdown of the polymer when exposed to negative microsecond impulse increases for liquid-polymer systems formed with the ester fluids as compare with that seen under positive voltage stress. Synthetic ester-DELRIN systems now show a 100% probability of experiencing bulk polymer breakdown, with systems that use the natural ester exhibiting a 60% probability of such breakdown occurring; this represents a 60% and 40% increase respectively. The probability of bulk breakdown of the polymer being experienced by the mineral oil-DELRIN composite is also observed to increase under negative energisation; despite no instances of this during testing under positive voltage stress, probability of the composite exhibiting this form of breakdown is now 60%. When bulk polymer breakdown is observed, the breakdown voltage and time to breakdown of all liquid-DELRIN composite systems are likely to be statistically similar. While bulk polymer breakdown is the predominant type of breakdown experienced by the liquid-DELRIN composites under negative energisation, systems formed with mineral oil or natural ester did suffer from interfacial flashover. Both these composite systems showed a 40% probability of this form of breakdown occurring, with the aforementioned insulating systems exhibiting a likely absence of statistical difference in both breakdown voltage and time to breakdown.

7.4. Breakdown of liquid-solid composite insulation under 0.4μs impulse

The subsequent sections of this chapter are given over to the presentation of results obtained from experimental work undertaken to determine how the breakdown characteristics of liquid-polymer composite insulating systems may be altered when stressed with impulses shorter than the standard lightning impulse. During the experimental study liquid-polymer composites formed from mineral oil (Shell Diala S4), synthetic ester (MIDEL 7131), natural ester (Envirotemp FR3) and practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with an identical nanosecond impulse (rise-time 0.4μs) as that used during the experimental work discussed in Chapter 6 of this thesis. As previously outlined (Section 7.2) the dielectric liquids were investigated in the ‘As Received’ condition; i.e. as supplied from the manufacturer. Breakdown voltage and associated time to breakdown was obtained when the composite insulating systems underwent flashover of the liquid-polymer interface or bulk breakdown of the polymer for the purpose of mean value analysis.

7.4.1. Breakdown of mineral oil-polymer composite insulation

Within this subsection the breakdown parameters (breakdown voltage and time to breakdown) obtained when composite insulating systems formed of the mineral oil (Shell Diala S4) and the four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with nanosecond impulse voltage will be presented and discussed. The testing methodology described in Section 3.6.2 was applied in all tests, where ten samples of each liquid-polymer combination were subjected to impulses of positive and negative polarity. Five samples were stressed with positive polarity nanosecond impulse, with the remaining five samples exposed to the same impulse of negative polarity. The breakdown voltage and time to breakdown of each liquid-polymer sample was analysed for mean values (when ten flashovers of the interface occurred) or stated if bulk breakdown of the polymer occurred.



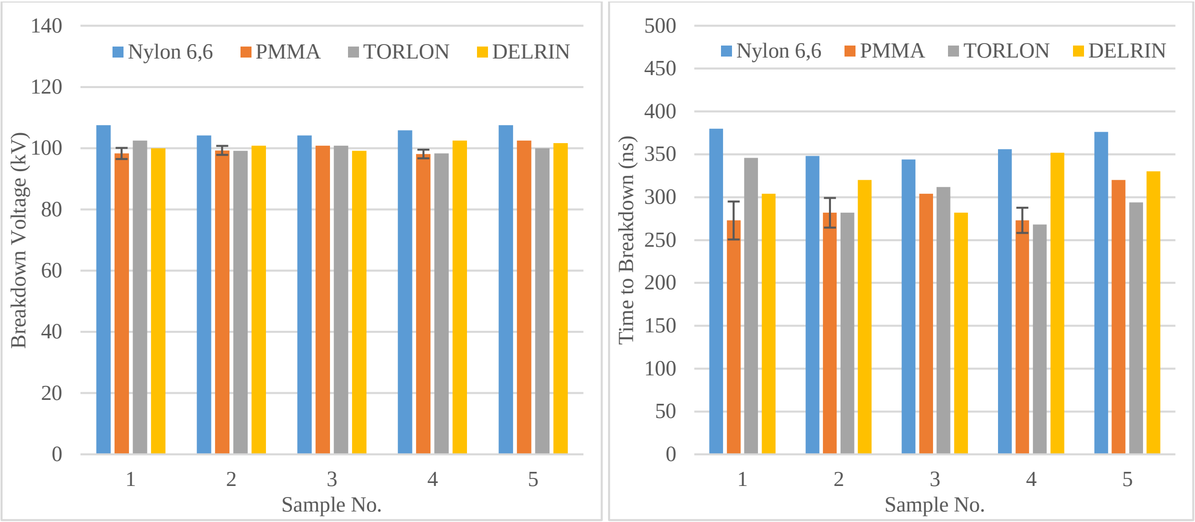
(a) (b)

Figure 7-13; *Positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltage data obtained when the mineral oil-polymer composite insulating systems were stressed with positive nanosecond impulse can be seen in Figure 7-13a. From the data presented it is clear that all mineral oil-polymer composites favour bulk breakdown of the polymer when exposed to the positive nanosecond impulse; occurring in 100% of tests irrespective of the polymer the mineral is paired with. Under such voltage stress, all mineral oil-polymer composite systems exhibit a similar breakdown strength with only an 11% difference in the highest and lowest levels of breakdown voltage;

observed for Sample 2 of the PMMA and DELRIN-based systems respectively. When evaluating the breakdown of a given mineral oil-polymer composite in isolation it can be said that systems formed of the PMMA polymer have the most consistent breakdown voltage, with only a 4% difference between highest and lowest values. Mineral oil-DELRIN composite systems demonstrate the greatest variability with a 10% difference in the breakdown strength of best and worst performing samples.

From Figure 7-13b it is clear that a greater variability exists in the time to breakdown of the mineral oil-polymer samples than was observed in the breakdown voltage data. When examining the highest and lowest values of time to breakdown obtained from testing, again associated with Sample 2 of the PMMA and DELRIN-based systems, it can be seen that the longest value is 55% greater than the shortest. This difference in values is 5 times that observed in the breakdown voltage of the samples, with this attributed to the breakdown of the PMMA-based sample occurring at the peak of the voltage impulse; a point at which the change in voltage is minimal but the change in time can be large. Unlike what was reported from the breakdown voltage data, when analysing the mineral oil-polymer composites in isolation it is now the TORLON-based systems, as opposed to those using the PMMA polymer, which exhibit the most consisted breakdown performance with a 27% difference in the longest and shortest time to breakdown. DELRIN-based composites again show the greatest variability in the required time to breakdown with the highest recorded value 56% above that of the lowest.



(a) (b)

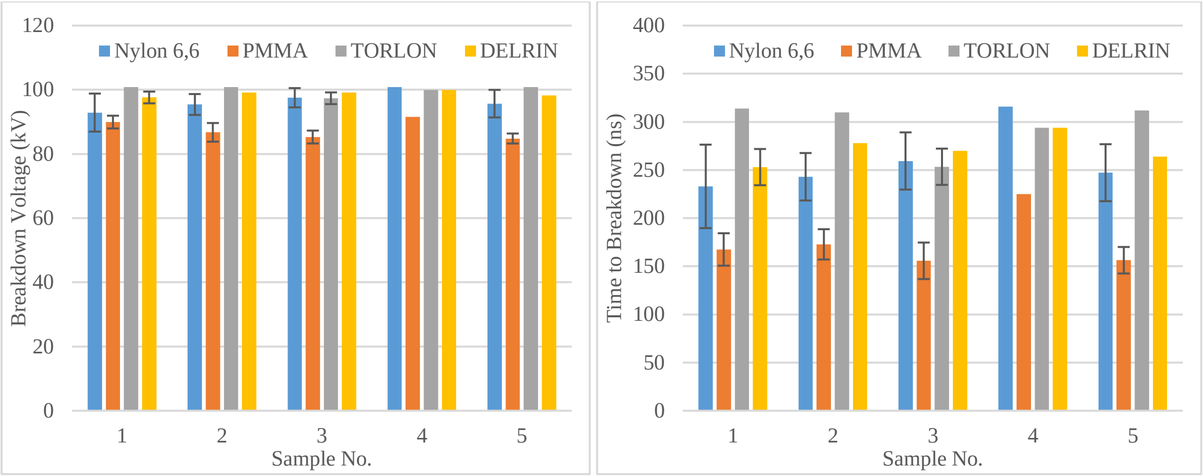
Figure 7-14; *Negative 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of the mineral oil-polymer composite insulating systems. Error bars represent standard deviation.*

When examining the breakdown voltage of the mineral oil-polymer composite insulating systems when stressed with negative nanosecond impulse it is evident that only the PMMA-based systems show a sensitivity to the polarity of the energising impulse. Under negative voltage stress the mineral oil-PMMA composite is now seen to favour interfacial flashover as opposed to the bulk breakdown of the polymer observed during testing with positive impulse voltage. All other mineral oil-polymer composite insulating systems show the same tendency for bulk breakdown of the polymer, occurring in 100% of tests, as was the case when the impulse was of positive polarity. Composite systems formed with the Nylon 6,6 polymer are shown to have the highest breakdown voltage when under negative nanosecond impulse, though as mentioned previously consistently experience bulk breakdown of the polymer. The lowest breakdown strength when bulk breakdown occurred was observed for the composite systems utilising the TORLON polymer. Interestingly the lowest value of breakdown voltage measured for a TORLON-based system (Sample 2) is below that of the mineral oil-PMMA composites that experienced interfacial flashover. When comparing the interfacial flashover voltage of the PMMA-based systems, the only mineral oil-polymer system to exhibit this form of breakdown, it can be said that a statistical difference in breakdown voltage is unlikely to exist between samples.

Once again, the time to breakdown measured for the mineral oil-polymer composite systems shows greater variability than that of the breakdown voltage. While the Nylon 6,6 composite systems still exhibit the highest values of time to breakdown the difference between the upper and lower values is ~10%, whereas only a 4% difference was observed in breakdown voltage. The same can be said for the mineral oil-TORLON composite systems, which have the shortest recorded time to breakdown, differences in the highest and lowest values of time to breakdown for this composite was seen to be 23% as compared with 4% in the breakdown voltage data. These discrepancies can once more be attributed to breakdown of the mineral oil-polymer composites taking place near the peak of the voltage impulse. From the samples of the PMMA-based composite that experienced interfacial flashover there is unlikely to be statistical difference in the time to breakdown from sample-to-sample.

7.4.2. Breakdown of synthetic ester-polymer composite insulation

The experimental data obtained when composite insulating systems formed of the synthetic ester (MIDEL 7131) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with nanosecond impulse voltage will be presented in the proceeding section. Liquid-polymer samples were exposed to impulses of both positive and negative polarity; five samples of a particular composite system for a given impulse polarity. Experimental data pertaining to the breakdown voltage and associated time to breakdown of the composite systems was logged and subject to post-experimental mean value analysis.

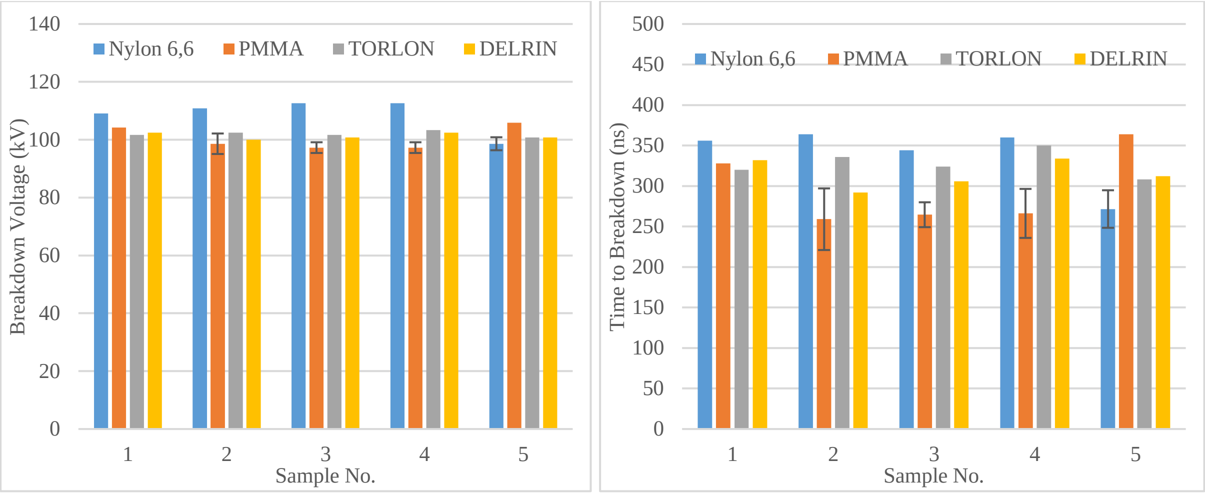


(a) (b)

Figure 7-15; *Positive 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.*

The breakdown voltage of the synthetic ester-polymer composite insulating systems when stressed with positive nanosecond impulse can be seen in Figure 7-15a. From the data shown it is evident that composite systems consisting to the synthetic ester and the TORLON and DELRIN polymers favour bulk breakdown of the polymer, with this occurring in 80% of tests involving these systems. Conversely, composite insulating systems formed of the Nylon 6,6 and PMMA polymer dielectrics show an 80% probability for interfacial flashover to occur. While only observed for one sample, the highest breakdown voltage was measured for the synthetic ester-Nylon 6,6 composite that experienced bulk breakdown of the polymer (Sample 4). That said, all synthetic ester-polymer composites that experience bulk breakdown demonstrate a similar dielectric performance with only a 9% difference between the highest and lowest recorded breakdown voltages; occurring for the aforementioned Nylon 6,6 composite and the same sample of the PMMA-based systems. When breakdown takes the form of interfacial flashover all synthetic ester-polymer systems expect those utilising the PMMA exhibit a level of breakdown voltage that likely demonstrates statistical similarity, with that of systems using the PMMA polymer statistically lower than all other composite systems.

The time to breakdown of the synthetic ester-polymer composite systems can be seen in Figure 7-15b. When examining the data it is clear that identical trends exist to those reported in the breakdown voltage data. Composite systems formed of the Nylon 6,6 polymer require the longest time to breakdown with those using the PMMA polymer the shortest, providing bulk breakdown of the polymer is observed. However, there is clearly higher variability in the recorded values of time to breakdown than is present in the breakdown voltage data with a 30% difference in the aforementioned values; as compared with only a 9% difference in breakdown voltage of these samples. Once again, when interfacial flashover occurs the PMMA-based systems required a time to breakdown statistically below that of all other composite systems experiencing this type of breakdown. When comparing the remaining composites for which interfacial flashover occurs it can be seen that all required a time to breakdown likely absent of statistical difference when placed under positive nanosecond impulse stress.



(a) (b)

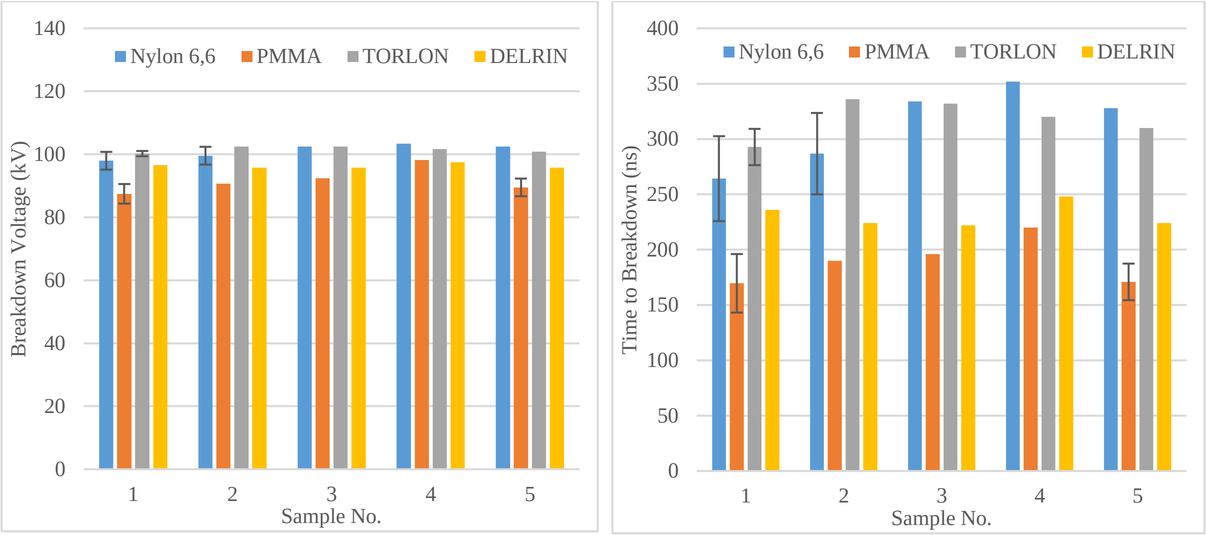
Figure 7-16; *Negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of the synthetic ester-polymer composite insulating systems. Error bars represent standard deviation.*

When evaluating the breakdown voltage of the synthetic ester-polymer composite insulating systems under negative nanosecond impulse voltage (Figure 7-16a) it is clear that all liquid-polymer composites, aside from those formed with the PMMA polymer, favour bulk breakdown. The probability of this form of breakdown taking place is seen to increase from the 80% observed during positive impulse tests to 100% for both the TORLON and DELRIN-based systems and 40% as compared with 20% for the PMMA systems, while remaining unchanged at 80% for the Nylon 6,6 composite. Once again, composite systems using the Nylon 6,6 polymer exhibit the highest breakdown voltage, 12% above that of those consisting of the DELRIN and TORLON polymers, which have the lowest dielectric strength. The only synthetic ester-polymer composite to favour interfacial flashover under negative nanosecond impulse stress are those formed with the PMMA polymer, occurring in 60% of tests. From Figure 7-16a it is clear that when interfacial flashover is observed there is a likely absence of statistical difference in the level of breakdown voltage measured for the composite systems.

The time to breakdown measured for the synthetic ester-polymer composite systems when stressed with negative nanosecond impulse can be seen in Figure 7-16b. From the data presented, it is clear that the time to breakdown data agrees well with that of the breakdown voltage of the composite systems under negative energisation. As with breakdown voltage composite systems utilising the Nylon 6,6 polymer required the longest time to breakdown, providing bulk breakdown of the polymer is observed. However, unlike what was reported for the breakdown voltage of samples that experienced bulk breakdown, only the TORLON-based systems are seen to require the shortest time to breakdown and not both the TORLON and DELRIN systems. This discrepancy is attributed to the closeness of the breakdown voltage of the TORLON and DELRIN samples that exhibit the lowest breakdown voltage and associated time to breakdown. As both samples had the same breakdown voltage, and the difference in time to breakdown was only 1%, this dissimilarity with what was reported in breakdown voltage is as a result of slight differences present in the energising impulse from test-to-test originating from parasitic elements in the impulse generating circuit. Again, when interfacial flashover occurs there is unlikely to be a statistically significant difference in the values of time to breakdown for any composite systems experiencing this form of breakdown.

7.4.3. Breakdown of natural ester-polymer composite insulation

This section of the chapter is dedicated to the presentation of experimental data pertaining to the breakdown of composite insulating systems formed of the natural ester (Envirotemp FR3) and the chosen solid polymers (Nylon 6,6, PMMA, TORLON and DELRIN) when stressed with nanosecond impulse. The effect voltage polarity has on the breakdown characteristics of the liquid-polymer composite insulation was evaluated by applying both positive and negative polarity impulse during the experimental study. Five samples of each composite system were exposed to a given impulse polarity. Experimental data on the breakdown voltage and associated time to breakdown of the composite systems was logged for the purpose of mean value analysis.



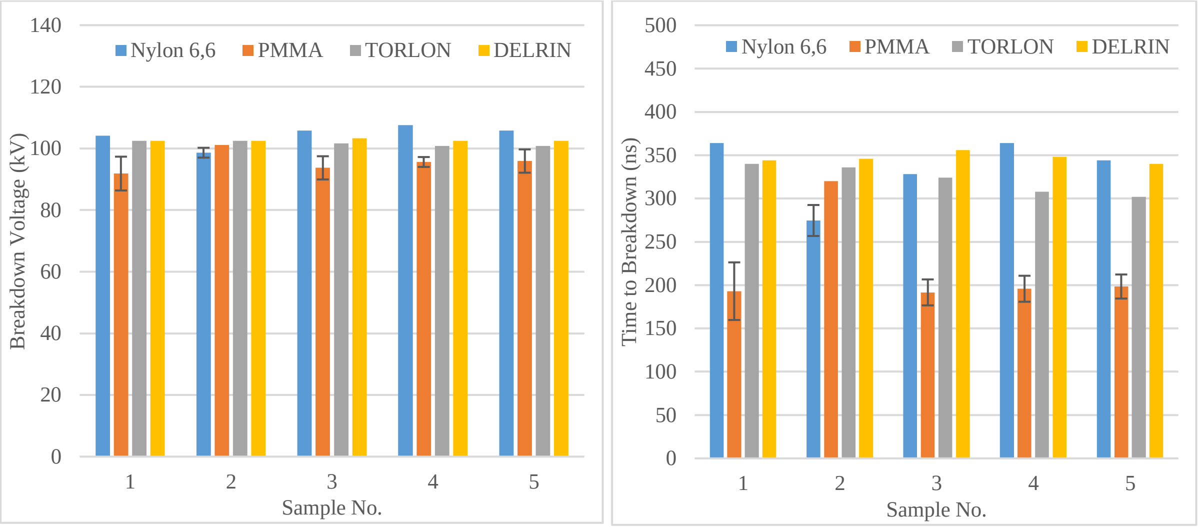
(a)

(b)

Figure 7-17; *Positive 0.4µs impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

It is clear that under positive nanosecond impulse all natural ester-polymer insulating systems favour bulk breakdown of the polymer, with this observed in 100% of tests involving the DELRIN polymer, 80% of those when the TORLON polymer was used and 60% conducted using both the Nylon 6,6 and PMMA polymers. While there is little variation in the individual breakdown voltages of the liquid-polymer composite samples that experienced bulk breakdown it can be said that those formed of the natural ester and Nylon 6,6 polymer exhibit the highest, and most consistent, breakdown voltage and those using the PMMA the lowest and most varied. When interfacial flashover of the composite system was observed it can be said that systems formed of the Nylon 6,6 and TORLON polymers require a level of voltage that is likely to be statistically similar to cause breakdown of the insulating system, while those utilising the PMMA polymer require a level of voltage statistically lower than the two aforementioned natural ester-polymer combinations. Interestingly, while the bulk breakdown voltage of the Nylon 6,6 and TORLON-based systems is above that of the interfacial flashover voltage of the other composites, systems using the DELRIN polymer consistently experience bulk breakdown of the polymer at a level of voltage below that of the interfacial flashover voltage of both the Nylon 6,6 and TORLON-based composites.

The time to breakdown of the natural ester-polymer composite insulating systems when stressed with positive nanosecond impulse can be seen in Figure 7-17b. It is clear from the figure that while the general trends in the data are the same as those seen within the breakdown voltage variability is much greater. Systems formed of the Nylon 6,6 polymer still exhibit the greatest dielectric strength, requiring the longest time to breakdown, but variability between sample values is much higher than was observed for their breakdown voltage; 5% as compared with ~1%. This can be attributed to breakdown of the aforementioned natural ester-polymer system occurring near the peak of the impulse, meaning the change in voltage is minimal compared to the change in breakdown time. Composite systems formed from the PMMA show the worst dielectric performance requiring the shortest time to breakdown for every sample tested irrespective of the type of breakdown experienced. Nylon 6,6 and TORLON-based insulating systems which experience interfacial flashover can be seen to require a time to breakdown that is likely to be absent of statistical difference for all samples for which this type of breakdown was observed.



(a) (b)

Figure 7-18; *Negative 0.4μs impulse (a) breakdown voltage and (b) time to breakdown of the natural ester-polymer composite insulating systems. Error bars represent standard deviation.*

The negative polarity breakdown voltage of the natural ester-polymer composite insulating systems when exposed to nanosecond impulse can be seen in Figure 7-18a. It is evident from the data presented that all liquid-polymer combinations expected those formed from the DELRIN polymer show a sensitivity to the polarity of the energising impulse. This susceptibility manifests for the Nylon 6,6 and TORLON-based composites as an increase in the probability of bulk breakdown of the polymer occurring, increasing by 20% for the aforementioned composites to 80% and 100% respectively. While the change in energisation polarity results in systems utilising the PMMA experiencing a reduction of 40% in the likelihood of experiencing bulk breakdown of the polymer. Under negative energisation composite systems using the Nylon 6,6 polymer once again exhibit the highest breakdown voltage and those formed with the TORLON the lowest; providing bulk breakdown is observed. When breakdown takes the form of interfacial flashover statistical difference in the breakdown voltage of the samples that experience this type of breakdown is unlikely given the overlap in the associated error bars.

When the time to breakdown of the natural ester-polymer composite systems is evaluated, it is clear that dissimilarities are present when compared to the data pertaining to the breakdown voltage of the test samples. While the Nylon 6,6 composite systems require the longest time to breakdown, as would be expected given they have the highest breakdown voltage, one sample is seen to require a time below that of the TORLON and DELRIN-based systems (Sample 3). This can be attributed to variability in the energising impulse caused by distortions originating from stray inductance and capacitance in the impulse generating circuit. When bulk breakdown is observed it is systems that utilise the TORLON polymer which require the shortest time to breakdown of the test samples, which is consistent with the observations made in the breakdown voltage data. Surprisingly, while there was a probable lack of statistical difference in the interfacial flashover voltage of the Nylon 6,6 and PMMA-based systems the latter is shown to require a time to breakdown statistically lower than the former.

7.4.4. Summary of the 0.4μs impulse breakdown of liquid-polymer composite insulation

The preceding sections (Section 7.4.1 to 7.4.3) were devoted to the presentation of the breakdown of composite insulating systems formed from the chosen dielectric liquids (mineral oil Shell Diala S4, synthetic ester MIDEL 7131 and natural ester Envirotemp FR3) and four practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) when exposed to nanosecond impulse stress. The work involved stressing the insulating systems with nanosecond impulses (rise-time 0.4μs) of both positive and negative polarity in the aim to ascertain the influence voltage polarity may exert on the breakdown performance of the composite insulating systems. The breakdown voltage and time to breakdown was recorded for liquid-polymer systems that underwent either ten individual interfacial flashover events or one single bulk breakdown of the polymer dielectric.

Table 7-5; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with positive 0.4μs impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	99.9 ± 1.7kV	100.6 ± 1.6kV	99.5 ± 1.4kV	98.6 ± 3.9kV
		296 ± 34ns	313 ± 33ns	283 ± 29ns	286 ± 57ns
	MIDEL 7131	100.8kV	91.5kV	101.9 ± 0.4kV	99.1 ± 0.7kV
		316ns	225ns	308 ± 9ns	277 ± 13ns
	Envirotemp FR3	102.8 ± 0.5kV	93.8 ± 3.9kV	101.9 ± 0.8kV	96.3 ± 0.8kV
		338 ± 13ns	202 ± 16ns	325 ± 12ns	231 ± 11ns
Interfacial Flashover	Shell Diala S4				
	MIDEL 7131	95.4 ± 4.4kV	86.7 ± 2.9kV	97.4 ± 1.8kV	97.6 ± 1.5kV
		246 ± 33ns	163 ± 18ns	253 ± 19ns	254 ± 17ns
	Envirotemp FR3	98.7 ± 2.9kV	88.5 ± 3.1kV	100.2 ± 0.8kV	
		276 ± 38ns	170 ± 22ns	293 ± 16ns	

The average levels of breakdown voltage and associated time to breakdown calculated for each of the liquid-polymer combinations when under positive polarity nanosecond impulse are provided in Table 7-5. Average values are stated ± the standard deviation calculated for the entire dataset of the given breakdown parameter. The size of a particular dataset is dependent on the number of breakdowns of a particular type recorded for a specific liquid-polymer insulating system. In the case of interfacial flashover the largest dataset is n = 50 (ten individual flashovers observed for all test samples), the smallest is n = 10 (when a single test sample underwent ten interfacial flashovers). When breakdown comes in the form of bulk breakdown of the polymer the maximum dataset is n = 5 (bulk breakdown of the polymer in all tests) with the minimum n = 1 (bulk breakdown occurs for a single sample). Standard deviation is not provided for datasets containing less than three data points; however mean value calculations were still performed on these datasets. Table entries devoid of data (greyed out) represent that no breakdowns of that type occurred for the given liquid-polymer composite system.

When the positive polarity nanosecond impulse breakdown of the liquid-Nylon 6,6 composites are evaluated it is clear that insulating systems formed of the polymer and the either the mineral oil or natural ester dielectric fluids show a tendency for bulk breakdown of the polymer; occurring in 100% and 60% of test respectively. Examination of the levels of voltage measured when bulk breakdown of the polymer is observed clearly shows that insulating systems form of the natural ester and the polymer offer a statistically higher breakdown voltage than those using the mineral oil. Given that only one instance of bulk breakdown of the polymer was observed in tests involving the synthetic ester it is not possible to directly compare the performance of this composite with that of the others investigated. However, it can be said that based on this single observation of bulk breakdown the synthetic ester-based composite offers a dielectric strength comparable to systems utilising both the mineral oil and natural ester fluids. From the data in Table 7-5 it is evident that the only Nylon 6,6 composite that favours interfacial flashover is that which utilises the synthetic ester as the dielectric liquid, with this form of breakdown observed in 80% of tests. When breakdown takes the form of interfacial flashover both esters perform similarly with a likely absence of significant difference in both breakdown voltage and associated time to breakdown.

Composite systems formed of the PMMA polymer and the dielectric fluids are seen to perform in a similar way to those formed with Nylon 6,6. Once again insulating systems that use either the mineral oil or natural ester fluids favour bulk breakdown of the polymer, occurring in 100% and 60% of tests respectively. Interestingly, the composite system that offers the best dielectric performance when bulk breakdown is observed is inverse to that of the Nylon 6,6-based composites, with insulating systems formed of the mineral oil and PMMA now exhibiting a breakdown voltage and time to breakdown statistically above that of the natural ester-based systems. Again, composites formed of the PMMA and synthetic ester cannot be directly compared with the others as bulk breakdown was only observed in a single test; though as can be seen in Table 7-5 this single bulk breakdown of the synthetic ester-PMMA system has a breakdown voltage, and time to breakdown, below that of the other composite systems. Interfacial flashover was the predominate from of breakdown observed when composites formed of the synthetic ester and PMMA polymer were stressed with positive nanosecond impulse, occurring in 80% of tests. This form of breakdown was also seen in 40% of test conducted with the natural ester-PMMA insulating systems, which exhibited a breakdown performance that can be assumed to be statistically similar to that of the aforementioned synthetic ester composite given the overlap in the associated standard deviation error bars.

TORLON-based composite systems can be seen to favour bulk breakdown of the polymer irrespective of the dielectric fluid used. This form of breakdown was observed universally for systems utilising the mineral oil and in 80% of tests involving the ester fluids. When bulk breakdown of the polymer is observed the mineral oil-based insulating system is shown to have breakdown voltage and time to breakdown statistically below both ester-based systems, while both composite systems consisting of the ester fluids offer a breakdown performance that is likely to be statistically similar to one another. When evaluating the performance of the insulating systems that experienced interfacial flashover it can be said that the natural ester-based composite systems offer a statistically better (higher) breakdown voltage and time to breakdown that those utilising the synthetic ester fluid.

Bulk breakdown of the polymer is also the predominate type of breakdown experienced by composite systems utilising the DELRIN polymer; observed in 100% of tests of the mineral oil and natural ester-based composites and 80% of those formed of the polymer and the synthetic ester. When comparing the breakdown parameters of the DELRIN-based composite systems it can be said that the mineral oil-based systems offer a breakdown performance likely to be statistically similar to both ester-based systems. However, the insulating systems formed with the synthetic ester have a breakdown voltage and an associated time to breakdown statistically above that of the composites using the natural ester fluid. The only liquid-DELRIN composite to experience interfacial flashover was the synthetic ester immersed system. When comparing the breakdown of this liquid-DELRIN composite system it can be seen that it offers a dielectric performance comparable to that of the systems that experienced bulk breakdown of the polymer, with the overlap of standard deviation error bars implying that statistical difference is unlikely.

Table 7-6; *Average breakdown voltage and time to breakdown of liquid-polymer composite insulating systems when stressed with negative 0.4μs impulse*

Breakdown Type	Liquid dielectric	Polymer dielectric			
		Nylon 6,6	PMMA	TORLON	DELRIN
Bulk Breakdown	Shell Diala S4	105.8 ± 1.7kV	101.6kV	100.1 ± 1.6kV	100.8 ± 1.3kV
		361 ± 16ns	312ns	300 ± 30ns	318 ± 26ns
	MIDEL 7131	106.3 ± 1.6kV	105kV	102 ± 1kV	101.3 ± 1kV
		356 ± 9ns	346ns	328 ± 16ns	315 ± 18ns
	Envirotemp FR3	105.8 ± 1.4kV	101.1kV	101.6 ± 0.8kV	102.8 ± 0.4kV
		350 ± 18ns	320ns	322 ± 17ns	347 ± 6ns
Interfacial Flashover	Shell Diala S4		98.6 ± 1.6kV		
			276 ± 18ns		
	MIDEL 7131	98.6 ± 2.3kV	97.7 ± 2.5kV		
		272 ± 23ns	267 ± 29ns		
	Envirotemp FR3	98.6 ± 1.6kV	94.3 ± 4.1kV		
		275 ± 18ns	212 ± 49ns		

Evaluation of the data presented in Table 7-6 has shown that the liquid-polymer composite systems have a sensitivity to the polarity of the energising impulse. When composite systems using the synthetic ester fluid are stressed with negative nanosecond impulse the probability of bulk breakdown occurring is increased as compared with when the impulse is of positive polarity, irrespective of the polymer dielectric used for the insulating system. A similar increase in the probability of bulk breakdown occurring is also experienced by composite systems formed from the natural ester and either the Nylon 6,6 or TORLON polymers, however when the PMMA polymer is used the likelihood of bulk breakdown is reduced as compare with stressing the composite with positive impulse. While the breakdown behaviour of the majority of mineral oil-polymer composites remains unchanged from what was observed under positive impulse stress, there is a reduction in the probability of bulk breakdown of the PMMA-based systems.

Composite systems consisting of the Nylon 6,6 polymer clearly favour bulk breakdown under negative nanosecond impulse stress, with this observed in 100% of tests when the polymer was paired with the mineral oil and 80% when the ester fluids were used. This represents an increase in the probability of this type of breakdown occurring when the polymer is immersed in either the synthetic ester of natural ester fluids of 60% and 20% respectively, while the behaviour of the mineral oil-based composite remains unchanged from what was observed under positive energisation. When bulk breakdown of the polymer is observed all liquid-Nylon 6,6 combinations exhibit what is likely to be a statistically similar breakdown performance, with this significantly higher than when interfacial flashover occurs. In the case that breakdown does come in the form of interfacial flashover, as is the case in 20% of the tests involving the ester fluids, it can be seen in Table 7-6 that there is unlikely to be a statistically significant difference in the breakdown parameters of the liquid-Nylon 6,6 composite insulating systems.

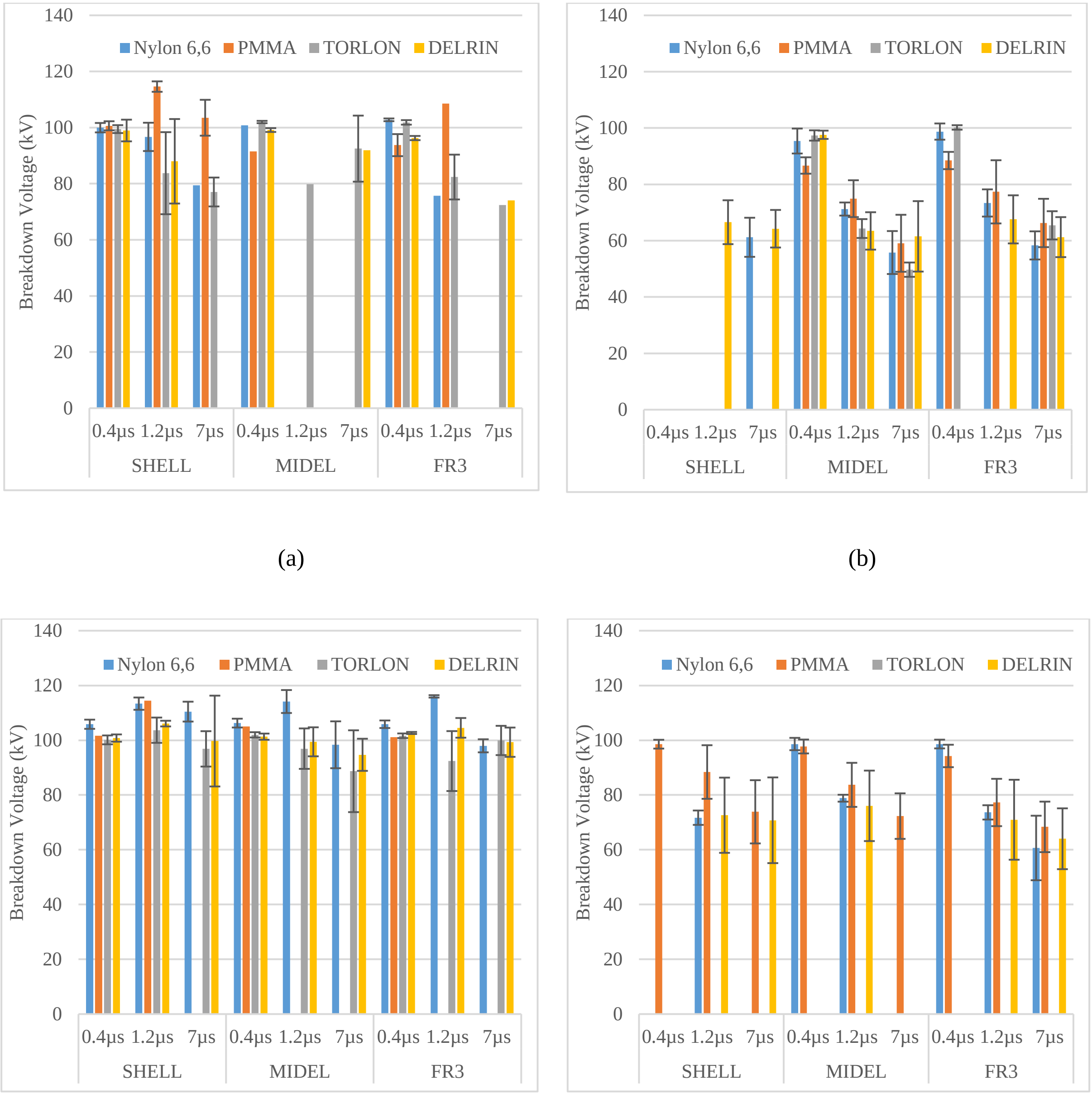
The behaviour observed for the PMMA-based composite systems when exposed to negative nanosecond impulse is seen to differ depending on the dielectric liquid used. While systems utilising the mineral oil or natural ester experience a reduction, of 60% and 20% respectively, in the likelihood of bulk breakdown occurring, systems formed with the synthetic ester see this probability increase by 20%. Given that only 20% of the natural ester-PMMA samples and 40% of those using the mineral oil or the synthetic ester experienced bulk breakdown it proves difficult to statistically compare breakdown performance, however as can be seen in Table 7-6 all liquid-PMMA composite systems exhibit equivalent breakdown voltages, with only a 4% difference between highest and lowest values. Under negative nanosecond impulse breakdown predominately takes the form of interfacial flashover, with this observed in 80% of tests using the natural ester and 60% when either the mineral oil or synthetic ester were the dielectric fluid. When comparing the breakdown parameters obtained when interfacial flashover was observed it can be said that statistical difference, at the selected degree of confidence, may not be present in the breakdown performance of all liquid-PMMA composite systems.

Under negative nanosecond impulse the breakdown of the TORLON-based composite insulating systems demonstrate a tendency for bulk breakdown of the polymer; with this observed in 100% of test samples irrespective of the fluid the polymer is immersed it. While this is identical behaviour to that observed for the mineral oil-TORLON systems under positive voltage stress, it represents an increase of 20% in the probability of either ester-based composite experiencing breakdown of the polymer dielectric. From the data provided in Table 7-6 it is clear that the standard deviation error bars for the breakdown voltage and time to breakdown for all liquid-TORLON composites overlap and thus statistical difference in these parameters is unlikely.

Bulk breakdown of the polymer dielectric is also universally observed for the liquid-DELRIN composite insulating systems no matter the dielectric fluid used. This behaviour mirrors that under positive nanosecond impulse for both the mineral oil and natural ester-based systems, while demonstrating an increase of 20% in the probability of the synthetic ester-DELRIN systems experiencing this form of breakdown. Composite systems consisting of the polymer and the natural ester fluid are seen to perform better than those formed of the other two dielectric fluids with a breakdown voltage statistically higher than that of the mineral oil and synthetic ester-based systems. However, when comparing the time to breakdown of the systems using natural ester and mineral oil statistical similarity is likely in the breakdown performance. This dissimilarity to the observation made in the breakdown voltage of the systems can be attributed to the small sample size (n = 5) used to calculate the mean value and associated standard deviation. Statistical similarity is also likely present in the breakdown voltage and time to breakdown of the mineral oil and synthetic ester-based systems.

7.5. Summary of the breakdown of liquid-polymer composite insulation

This chapter of the thesis was used to present and discuss results obtained during experiments conducted to investigate the breakdown characteristics of liquid-polymer insulating systems under conditions applicable to pulsed power machines. To that end composite insulating systems formed of mineral oil (Shell Diala S4), synthetic ester (MIDEL 7131) and natural ester (Envirotemp FR3) paired with practical polymers (Nylon 6,6, PMMA, TORLON and DELRIN) were stressed with both standard lightning (1.2/50µs) and non-standard (rise-time of 7µs and 0.4µs) HV impulses. The influence of impulse polarity on the observed breakdown characteristics of the liquid-polymer insulating systems was also investigated with both positive and negative impulses used during the experimental study. For each liquid-polymer sample breakdown parameters (breakdown voltage and time to breakdown) were logged for ten individual interfacial flashovers, or a single bulk breakdown of the polymer dielectric. Applying such a methodology allowed for determination of both the level of voltage required to cause complete breakdown of the composite insulating system, as well as providing an indication of the likelihood of the different types of breakdown to occur.



(a) (b)

(c) (d)

Figure 7-17; *Average positive breakdown voltage (a) when interfacial flashover occurs and (b) bulk breakdown occurs and average negative breakdown voltage (c) when interfacial flashover occurs and (d) bulk breakdown occurs, for all liquid-polymer composite insulating systems. Error bars represent standard deviation.*

It is clear from the data presented relating to the levels of positive impulse voltage required to cause either bulk breakdown of the polymer constituent of the composite insulating system (Figure 7-17a) or flashover of the liquid-polymer interface (Figure 7-17b) that irrespective of the rise-time of the impulse composite systems formed of the polymers and mineral oil favour bulk breakdown of the polymer. This is most apparent when composites are formed of the mineral oil and PMMA polymer, for which only bulk breakdown of the polymer was observed under positive voltage stress. Given the electronegative properties of mineral oil, free electrons will not be readily available within the bulk liquid to drive ionisation, therefore it is postulated that these electrons are draw from the bulk of the solid material and thus guide the propagation path of any developed ionisation front(s) (streamer(s)) into the bulk of the solid dielectric. This is confirmed when comparing against the breakdown of the mineral oil-PMMA composite systems under negative impulse (Figure 7-17c and 7-17d) where probability of bulk breakdown of the PMMA polymer is reduced as compared with when in composite was stressed with positive voltage. This is due to electrons being injected from the tip of the HV electrode under negative energisation which negates the need for them to be drawn from the volume of the solid dielectric. Furthermore, as discussed in the work by [103], the ‘interfacial permittivity ratio’ of the mineral oil-PMMA, as well as all other mineral oil-polymer composites, is <1 (relative permittivity of the solid > than that of the liquid), resulting in enhancement of the electric field in the vicinity of the HV electrode. It is assumed that under positive voltage this field enhancement further drives the streamer into the volume of the solid dielectric and thus results in the streamer propagating through the bulk of the solid; ultimately resulting in the breakdown of the solid dielectric. While under negative energisation the density of the space charge formed in and around the triple junction results in a drop in the nominal electric field strength in this region and effectively increases the stress on the liquid-polymer interface. For certain liquid-polymer composites systems, such as those formed with the PMMA polymer, this increased field stress on the liquid-polymer interface encourages surface flashover, however for others it increases the probability of bulk breakdown of the polymer occurring.

Examination of post-breakdown polymer samples exposed to negative impulse has confirmed that ingress of the streamer into the bulk of the polymer does not always occur at the point which the HV needle electrode makes contact with the polymer surface. It was found that a number of samples had puncture holes several millimetres from the triple junction point; this observation supports the assumption that the point of peak electric field is shifted from the HV needle due to space charge effects. This phenomenon was most commonly observed in the Nylon 6,6 polymer samples which is the material with the highest degree of porosity of the four investigated solid dielectrics. From this, it can be concluded that streamer(s) are drawn into the bulk of the solid material due to high field stress on the surface coupled with the breakdown of gas-filled voids within the bulk of the material. Streamers are then free to propagate through the bulk of the solid material with this driven by further breakdown of gas-filled voids.

However it was not only composite systems placed under negative voltage stress that experienced bulk breakdown of the polymer, this was also observed for samples exposed to positive impulse. However, the majority of these instances of bulk breakdown under positive voltage stress occurred when the shortest (rise-time of 0.4µs) impulse was applied to the liquid-polymer composite system. Given the arrangement of the HV and GND electrodes (See Section 3.4.2.2) it is postulated that this result is due to an effect similar to that seen in electrical discharge drilling (EDD) experiments. In [151] it was reported that the drilling capability of an electrical spark discharge is enhanced as the rise-time of the impulse is shortened. Given that the majority of bulk polymer breakdown observations were made during exposure of the composite samples to the shortest impulse, which is in the range of impulses used in plasma drilling tests (0.05 – 0.5µs [151]), it is reasonable to assume that such a mechanism could be responsible for the observation made during experimentation. Furthermore, in [152], [153] it was shown that EDD efficiency is improved with the use of negative polarity impulse due to the increase in local heating and erosion of the solid when struck with high velocity electrons. This may explain the favourability shown by the liquid-polymer composite insulation for bulk breakdown under negative energisation.

Chapter 8 – Conclusions and further work

8.1. Introduction

The work conducted for this thesis focused on the investigation of the breakdown performance of ester dielectric liquids, both natural and synthetic, and ester liquid-polymer composite insulating systems when stressed with impulse voltages. The study was undertaken with the intention to systematically study the breakdown performance of these environmentally friendly dielectric liquids under test conditions that would lead to increased confidence in the use of these fluids within not only the power but also the pulsed power industry. Given that mineral oil is the predominate insulating fluid used within these industries all experimental results obtained for the ester fluids and ester liquid-polymer composite systems were evaluated against those for mineral oil and mineral oil-based composites tested under identical experimental conditions. In order to yield useful information for pulsed power operators it was not possible simply to stress the fluids with the standard lightning impulse, as is the case in power industry standard breakdown tests, rather a number of discrete impulses were utilised during the experimental study. Namely, one shorter (0.4μs rise-time) and one longer (7μs rise-time) than the standard lightning impulse (1.2μs rise-time), which was also utilised as a means of comparing the observed breakdown performance of the fluids with that widely reported within literature. To ensure the provision of a comprehensive evaluation of the breakdown performance of the three dielectric fluids it was important to conduct tests under both positive and negative voltage stress, given the varied breakdown mechanisms associated with a given impulse polarity. Further to this the effect moisture content of the dielectric liquid has on bulk breakdown performance was also evaluated. Examination of the effect this particular parameter has on impulse driven breakdown is lacking in published literature and thus was an important inclusion within the thesis as it can yield vital information for designers and operators of power and pulsed power assets.

Also contained within this thesis is a study of the breakdown performance of composite liquid-polymer insulating systems formed of ester fluids and practical solid polymers as well as the same polymers paired with mineral oil. This work is important as the majority of published research work in this area relates to the types of composite used in transformers (liquid-paper systems) and given that these are now used within pulsed power machines the findings from previous studies are not applicable to the pulsed power industry. To ensure this was addressed within the work conducted for this thesis the composite insulating systems were stressed with the same three discrete impulses used within the bulk liquid breakdown study, again with both positive and negative impulses utilised during experimental work. Further to this the breakdown study did not only record the breakdown parameters of test samples for which interfacial flashover was observed but also those experiencing bulk breakdown of the polymer dielectric. Adoption of such an approach allowed for information to be gathered on both the level of voltage required to cause breakdown of the composite insulating system as well as the probability of the given liquid-polymer composite experiencing a particular type of breakdown. This will prove to be of great use to designers of electrical machines as it can be used to influence coordination of insulation as to reduce the likelihood of catastrophic failure through bulk breakdown of polymer supporting structures.

8.2. Conclusion of the bulk liquid breakdown study

This work investigated the bulk breakdown performance of synthetic ester MIDEL 7131 (M&I Materials Ltd, UK), natural ester Envirotemp FR3 (Cargill, USA) and mineral oil Shell Diala S4 (Shell Ltd, UK) when stressed with both standard (1.2µs rise-time) and non-standard (0.4µs & 7µs rise-times) voltage impulses. As the experiments were conducted using a needle-sphere electrode configuration, to facilitate a highly divergent electric field, impulses of both positive and negative polarity were used during tests to evaluate how breakdown behaviour of the fluids may differ with impulse polarity. The effect of the relative moisture content of the fluid on breakdown strength was also examined, with fluids tested in three discrete levels of relative humidity. The first of these ‘As Received’ represents fluids with moisture content as provided by the manufacturer, the next ‘Ambient humidity’ denotes fluids that were left in open containers within the laboratory to allow relative humidity to reach an equilibrium with ambient levels (RH ~35%), and the final state ‘Elevated humidity’ where fluids were subjected to a process of humidification to increase relative humidity significantly (RH >70%).

From the experiments involving the stressing of the bulk dielectric fluids with positive lightning impulse it can be said that the mineral oil and synthetic ester may have a statistically similar dielectric strength when in all but the highest state of relative humidity; with this also the case for the natural ester in the 'As Received' condition, while in all others states breakdown of this fluid occurs at a statistically lower voltage than mineral oil. This finding cannot be attributed to the effect of water content on dielectric strength as for a given dielectric liquid it has been shown that irrespective of moisture content statistical differences in breakdown voltage cannot be confirmed at the selected level of confidence. It is postulated that these findings are a result of the specific samples sizes used within tests and how this effects the calculated confidence intervals, were the sample size to be increase it can be assumed that all liquids would likely exhibit a statistically similar breakdown strength. Due to the methodologies applied in most published research work, predominately those outlined in IEC 60897 and ASTM D3300, where only one breakdown event occurs before a liquid sample is change it is not a straightforward task to compare results with those already published. It is clear however, that under positive lightning impulse both natural ester and synthetic ester fluids offer comparable dielectric performance to that of mineral oil. From the time to breakdown data obtained under positive lightning impulse it was shown that while streamers in mineral oil did propagate slower than those in ester fluids, all show average velocities characteristic of 3rd mode streamers, however further corroboration of this is required given that both statistical and formative time are not accounted for in this analysis.

When the lightning impulse is of negative polarity, again the mineral oil has a higher breakdown voltage ~4% and ~5% above that of the synthetic ester and natural ester fluids respectively. That said as the confidence intervals of the data overlap in all case these differences may not be statistically significant at the selected level of confidence. Once again it was shown, that under the applied experimental conditions, when the moisture content of a given dielectric liquid is increase there is no effect on the dielectric strength of the liquid. The measured time to breakdown for each of the liquids under negative lightning impulse again implies that in the case of the overstressed energisation regime (when breakdown voltage is lower or equal to the nominal peak voltage of the applied impulse waveform and development of the streamers is governed by the initiation conditions) streamers propagate slower in mineral oil than in ester fluids. It was established that average velocities of streamers in mineral oil corresponded to the upper 2nd mode while all streamer average velocities in both the synthetic ester and natural ester liquids were characteristic of the faster 3rd mode, again though further analysis is needed to confirm this, during which statistical and formative time will be taking into account.

When the dielectric fluids were subjected to the longer (7μs rise-time) impulse differing dielectric behaviour is observed to that reported under standard lightning impulse stress. When the impulse is of positive polarity, the natural ester is shown to have a statistically higher breakdown voltage than both the mineral oil and synthetic ester fluids; ~16% above the mineral oil and ~75% greater than the synthetic ester. Under positive voltage stress the synthetic ester MIDEL 7131 experiences a stark drop in breakdown voltage after the occurrence of the first breakdown of the fluid. As aforementioned due to the testing procedures adopted in other published work reports of similar behaviour could not be found in literature and thus this requires further investigation. Again, the relative moisture content has been shown to exert no influence on the breakdown strength of the dielectric fluids. The time to breakdown of the dielectric fluids under positive microsecond impulse imply that the average velocity of ionisation front(s)/streamers within the natural ester and mineral oil corresponds to slower 2nd mode, while in the synthetic ester the average velocity corresponds to faster 3rd mode of streamer development.

When the longer impulse was of negative polarity inverse behaviour of the ester fluids is observed as compared with when the impulse is positive. Under negative energisation, the synthetic ester now has the highest breakdown voltage, above that of the mineral oil, while the natural ester now exhibits the lowest breakdown strength of the three fluids. However, given the size of the confidence intervals of the mineral oil and synthetic ester data the difference in breakdown strengths of these fluids may not be statistically significant at the selected level of confidence. Once more moisture content is shown to have no effect on the breakdown of the dielectric liquids. Under negative impulse all liquids are shown to develop streamers with an average velocity which corresponds to the slower 2nd mode, with those propagating in the synthetic ester seen move at the slowest speed.

When the shortest of the energising impulses was utilised the breakdown behaviour is again altered from that observed under the other two investigated impulses. When the experimental data obtained for positive impulse tests is examined in its entirety, while the mineral oil has the highest observed breakdown voltage, statistical difference in measured levels of breakdown voltage for the given liquids may not be present at the selected degree of confidence, irrespective of relative humidity. When the data for the three liquids at a given humidity level is assessed in isolation a clear, statistical, difference is apparent between the breakdown voltages of the two ester fluids and the mineral oil; with this fluid clearly seen to exhibit statistically higher levels of breakdown voltage in both the 'As Received' and 'Ambient humidity' conditions. Again, the moisture content of a given dielectric fluid is shown to have no effect on the level of voltage required to cause liquid breakdown. From the time to breakdown data it can be inferred that while all liquids promote the development of 3rd mode streamers. Streamers developed under positive nanosecond impulse in mineral oil propagate as ~50% of the velocity of those in both natural ester and synthetic ester liquids. Again, as in the case of all streamer propagation modes obtained in the present work, classification is based on the average velocity; however as discussed previously (Section 2.3.4.3) streamers can accelerate or decelerate during their development, thus the accurate investigation of streamer velocity in the overstressed initiation controlled breakdown regime is a challenging task which requires further investigation with the use of high speed iCCD camera(s).

Under negative nanosecond impulse stress it was not possible to achieve overstressed breakdown (breakdown on the rising edge of the impulse) of the mineral oil at the level of voltage used in all other tests, this resulted in the nominal output voltage of the impulse circuit being increased from 150kV to 175kV. While this did allow for breakdown of the mineral oil to be achieved, it occurred on the plateau of the energising impulse rather than the rising edge. Given the safety concerns that would have arisen from increasing the output of the impulse circuit above 175kV the discussion was taken to use breakdown data obtained at this level for comparison with the ester fluids. Due to the point at which breakdown of the mineral oil took place on the energising impulse there was minimal variation in the voltages measured for each breakdown event. Unsurprisingly the mineral oil exhibited a statistically higher breakdown voltage than the other two fluids, ~16% above that of the synthetic and natural ester fluids; with these two liquids requiring a level of voltage to result in breakdown that can be assumed to be statistically similar to one another, irrespectively of the liquid moisture content. Relative humidity again was observed to exert no influence on the dielectric strength of any of the dielectric liquids. Similar to the observation made under positive stress, streamers developed in mineral oil under nanosecond impulse propagate at ~50% of the velocity of those in natural ester and synthetic ester fluids.

When evaluating how the three dielectric liquids are affected by alteration of the wave-front time of the energising impulse it is clear that dissimilarity exists between the response of the mineral oil and ester fluids to a change in nominal rise-time. Under both the shortest (0.4µs rise-time) and standard lightning impulse the mineral oil has the highest breakdown voltage irrespective of impulse polarity, with both ester fluids exhibiting similar levels of breakdown voltage. This however is not the case when the longest (7µs rise-time) impulse is applied to the fluids. Under this long impulse the mineral oil always performs worse than one of the ester fluids; with breakdown voltage lower than the natural ester under positive impulse and the synthetic ester under negative voltage stress. Given the length of the impulse rise-time, it is postulated that this results from breakdown being driven not solely by ionisation fronts but also by the formation of low-density regions (bubbles). As this form of breakdown requires the localised heating of the fluid it can be assumed that the much higher boiling point of the ester fluids acts to restrict the formulation of these low-density regions and thus requires an increased level of electric field (voltage) to cause breakdown of the fluid.

The comparable breakdown voltage of both natural ester and synthetic ester fluid with that of mineral oil means that, from an energy density perspective, ester fluids outperform mineral oil. Given that energy density is the product of relative permittivity and the square of electric field, in this case average electric fluid value is used ($0.5\cdot\varepsilon_0\varepsilon_r\cdot E_{Av}^2$), the higher relative permittivity of the ester fluids results in a fluid with greater energy density. For example, when stressed with negative lightning impulse ‘As Received’ natural ester and synthetic ester fluids offer energy densities ~34% and ~29% higher respectively than mineral oil under the same test conditions.

It is clear from the data presented that in almost all cases evaluated in the work of this thesis that both natural and synthetic ester fluids offer similar bulk breakdown performance to that of mineral oil under impulse voltage stress; at times even surpassing the dielectric strength of this conventional insulating fluid. This demonstrates that ester fluids are a viable alternative to mineral oil when they are to be used in operational scenarios similar to those investigated within the experimental work described in this thesis.

8.3. Conclusion of liquid-polymer interfacial breakdown study

The other main research effort discussed in this thesis was an experimental investigation into the breakdown of liquid-polymer interfaces when under impulse voltage stress. During the study interfaces formed from the three dielectric fluids used during the bulk liquid breakdown investigation (MIDEL 7131 synthetic ester, Envirotemp FR3 natural ester and Shell Diala S4 mineral oil) and practical polymer dielectrics (Nylon 6,6, PMMA, DELRIN and TORLON) were stressed with the same impulses applied to the bulk liquids (0.4µs, 1.2/50µs lightning and 7µs). The composite insulating systems were exposed to a highly divergent electric field and thus both positive and negative impulses were used during tests to ascertain what influence polarity may have on breakdown dynamics. In response to the negligible effect of moisture content on the bulk breakdown of the dielectric liquids, fluids were evaluated in the ‘As Received’ condition throughout this experimental work.

When the composite insulating systems were stressed with standard lightning impulse it can be said that statistically significant variations may not exist in breakdown voltage as a result of changing the liquid the polymer is immersed in; providing interfacial flashover occurs. Breakdown of the polymer dielectric consistently occurs at a higher voltage level than is observed during interfacial flashover of the same material; with breakdown under negative impulse requiring a higher voltage in all cases as compared with positive impulse. Irrespective of voltage polarity, composite systems consisting of a chosen dielectric liquid and the PMMA polymer exhibit a higher breakdown voltage than when the same liquid is paired with the other polymers. Interfaces formed with DELRIN are consistently observed to exhibit the lowest interfacial flashover voltage under both positive and negative energisation.

Some polarity dependant behaviour was observed however, with both the Nylon 6,6 and DELRIN polymers seen to react to impulse polarity with likelihood of bulk breakdown of the polymer increased when the impulse is negative. Breakdown of the DELRIN polymer was seen to increase when the impulse is negative as compared with positive; occurring in 60% and 20% of tests respectively. Under negative energisation Nylon 6,6 samples show equal likelihood of solid breakdown (80%) irrespective of the liquid it is immersed in, however when the lightning impulse is positive this form of breakdown is only observed in those samples immersed in either the natural ester (20% of samples) or the mineral oil (100% of samples). Interfaces formed with the TORLON polymer clearly favoured breakdown of the polymer with this occurring in ~95% of positive and 100% of negative impulse tests. Composites formed with the PMMA polymer clearly favour flashover of the interface, particularly under negative energisation (53% positive, ~95% negative).

From the data obtained on the breakdown of the liquid-polymer composites under positive 7µs impulse no significant change in the breakdown voltage exists between samples immersed in a given liquid providing interfacial flashover, rather than bulk polymer breakdown, occurs. The highest measured levels of breakdown voltage under positive impulse were recorded for liquid-polymer samples which experienced bulk breakdown of the polymer. The probability of a given polymer to experience a particular type of breakdown (interfacial flashover or polymer breakdown) is observed in some cases to be dependent on the surrounding liquid. For example, the PMMA polymer, clearly favours interfacial flashover when immersed in the ester fluids and bulk breakdown in mineral oil. While in the case of both the Nylon 6,6 and DELRIN polymers probability of interfacial flashover is comparable for all liquid-polymer combinations. Composite systems consisting of the TORLON polymer are also seen to exhibit differences in breakdown performance when submerged in the varying fluids. Differing behaviour is observed for all three liquid-TORLON systems; with samples immersed in natural ester exhibiting much higher probability of interfacial flashover (80% of tested samples), synthetic ester showed a tendency towards bulk breakdown of the polymer (60% of tested samples), while mineral oil clearly favoured polymer breakdown (100% of tested samples).

When examining the breakdown voltages measured when the composite systems were exposed to negative 7µs rise-time impulse differing behaviour (as compared with positive impulse) is observed in almost all tests. Firstly, negative breakdown consistently occurs at a higher level of voltage for a given liquid-polymer composite than when under positive stress. Though as with the positive impulse tests, statistical difference is unlikely to exist in breakdown voltage for a given liquid-polymer composite irrespective of chosen liquid; providing surface flashover occurs. Levels of voltage required to cause complete breakdown of a given polymer show dependence on the liquid the polymer is immersed in. Taking polymers immersed in synthetic ester MIDEL 7131 as an example, the highest average breakdown voltage was recorded for the Nylon 6,6 polymer samples, while the highest single breakdown voltage was recorded for the TORLON polymer. Under negative impulse it is clear that the probability of a given polymer experiencing bulk breakdown is greatly increased as compared with the same sample under positive stress, irrespective of the liquid it is submerged within; true for all cases except the PMMA polymer for which interfacial flashover occurred for all liquid-PMMA samples tested. Bulk breakdown probability for the Nylon 6,6 polymer is seen to greatly increase for all liquids where now all polymer samples experience bulk breakdown, a similar increase is also observed for the DELRIN polymer with bulk polymer breakdown observed in all but one test. Interfaces formed with TORLON again have the greatest probability of experiencing polymer breakdown; with this occurring in 100% of tests irrespective of the liquid used to immerse the polymer samples.

Under positive 0.4µs rise-time impulse the Nylon 6,6 and PMMA-based composites exhibit breakdown behaviour dependant on the dielectric liquid used, with those utilising the mineral oil or natural ester favouring bulk breakdown of the polymer while those employing the synthetic ester have a tendency for interfacial flashover. Composite systems formed with the TORLON polymer once again favour bulk breakdown of the polymer irrespective of the dielectric liquid used; occurring in 100% of tests when mineral oil was paired with the polymer and 80% of those when the ester fluids were used in the composite system. DELRIN-based composite insulating systems also favour bulk breakdown of the polymer when under 0.4µs positive impulse; occurring in 100% of tests when the polymer was in contact with mineral oil or natural ester and 80% of those when paired with the synthetic ester liquid. The highest levels of breakdown voltage under positive nanosecond impulse stress were measured for the natural ester-Nylon 6,6 composite when bulk breakdown of the polymer took place; however when the same fluid was paired with the PMMA polymer bulk breakdown occurred at the lowest voltage observed for composites experiencing this form of breakdown. Only ester-based composite insulating systems were observed to experience interfacial flashover under positive nanosecond impulse, with those formed with the Nylon 6,6 polymer offering the highest dielectric strength and those consisting of the PMMA the lowest.

Under negative 0.4µs rise-time impulse stress the composite systems consisting of the Nylon 6,6 polymer favour bulk breakdown of the polymer irrespective of the dielectric liquid used. This represents a change in behaviour for the systems formed with the synthetic ester, which predominately experienced interfacial flashover under positive voltage stress. Composite liquid-PMMA insulating systems also show differing behaviour under negative energisation, now favouring interfacial flashover as opposed to bulk breakdown of the polymer, irrespective of the dielectric liquid used in the insulating system. TORLON-based composite insulating systems again demonstrate a tendency of bulk breakdown, with this observed in 100% of tests. This is identical behaviour to that observed when the composite systems were placed under positive nanosecond impulse stress. The probability of the DELRIN-based composite systems to experience bulk breakdown is also increased under negative nanosecond impulse, with this form of breakdown observed in 100% of the tests involving this polymer. The highest levels of breakdown voltage seen under negative nanosecond impulse were observed for the Nylon 6,6-based composite systems, for which there was a probable lack of statistical difference in dielectric strength of the combinations using this polymer. Similarly, when interfacial flashover is observed there is unlikely to be a statistical difference in breakdown voltage of any of the liquid-polymer combinations that experienced this form of breakdown.

8.4. Major research findings

From the work undertaken during this thesis a number of key research finding have been made, these can be summarised as follows:

- Moisture content of the fluid has no significant effect on the breakdown behaviour of ester fluids, natural or synthetic, or mineral oil when stress with any of the impulse voltages (wave-shape or polarity) used in this study.

- Natural and synthetic ester fluids offer comparable dielectric performance to that of mineral oil when stressed with a range of different impulse voltages. It was shown that for all cases, except negative polarity nanosecond impulse, that both natural and synthetic ester fluids have comparable, most likely statistically similar, breakdown parameters to that of mineral oil.
- Ester fluids, both natural and synthetic, have proven to provide higher energy densities than mineral oil when under identical voltage stress. This finding supports the use of ester fluids within pulse forming lines, a key component in pulsed power apparatus.
- When stressed with impulses of rise-time longer than that of the standard lightning impulse ester fluids offer superior dielectric strength to that of mineral oil. The specific ester that outperforms mineral oil is dependent on the polarity of the energising impulse, with natural ester Envirotemp FR3 superior under positive voltage stress and synthetic ester MIDEL 7131 when the impulse is of negative polarity.
- When acting in conjunction with practical polymers as part of a composite insulating system ester liquids encourage the occurrence of flashover across the liquid-polymer interface while mineral oil promotes bulk breakdown of the polymer.
- Composite insulating systems formed with Nylon 6,6 or DELRIN polymers show a sensitivity to impulse polarity, with breakdown of the polymer favoured under negative impulse and interfacial flashover under positive. Composites using the PMMA polymer show a similar yet inverse tendency when paired with mineral oil.
- The rise-time of the energising impulse exerts an influence on the type of breakdown experienced by a liquid-polymer insulating system, with probability of bulk breakdown of the polymer observed to increase when the rise-time of the impulse is reduced.

8.5. Major contributions made with research work

The work conducted throughout the research project has made a number of major contributions to the wider understanding of the dielectric behaviour of insulating fluids including natural and synthetic esters and mineral oil. These can be summarised as the following:

- This programme has provided important information to researchers and practitioners through a comprehensive study of ester liquids (natural and synthetic) and mineral oil. Determining their bulk breakdown performance when stressed with impulses of rise-times applicable to pulsed power machines (0.4µs, 1.2µs and 7µs rise-time), as well as how this may be affected when the liquids are used in composite liquid-polymer insulating systems.
- A comprehensive investigation studying the effect of rise-time on the breakdown strength of these fluids was conducted. Within this study three independent wave-front times were used; 0.4µs, 1.2µs lightning and 7µs. Use of such a range of wave-front times allowed for accurate Volt-Time breakdown characteristics to be derived for both the bulk performance of ester fluids and when acting as part of a liquid-polymer composite system.
- The breakdown tests conducted represent different types of voltage stress experienced in operational pulsed power machines. This will help to overcome a lack of this information within literature, removing the barriers to the adoption of environmentally friendly insulating liquids within the pulsed power industry.
- Due to the lack of published research discussing how impulse breakdown performance is affected when the examined fluid is in a heightened state of relative humidity this programme involved a comprehensive study of the affect relative moisture content of the fluid has on the impulsive breakdown characteristics of both natural and synthetic ester fluids as well as conventional mineral oil. Within this study three discrete states of relative humidity were evaluated; ‘As Received’ ~10%, ‘Ambient’ ~35% and ‘Elevated’ >70%.
- During all breakdown experimentation time to breakdown has been reported. Given this is currently not required by international standard testing methodologies there is a lack of information pertaining to the time to breakdown of both ester fluids and mineral oil, which the work presented in this thesis has addressed.

8.6. Further work

Upon completion of the research programme a number of unexplored areas have been identified as those which represent possibility for further work

- The investigation into the effect of fluid moisture content could be extended to include both ‘dry’ liquids and liquids near their individual moisture saturation limits. This would provide unequivocal evidence that the moisture content of a dielectric liquid exerts no influence on breakdown performance under impulse voltage stress.
- Confirmation of the individual breakdown mechanisms assumed to be responsible for bulk breakdown of the dielectric fluids could be confirmed through the implementation of a high-speed camera during experimentation. This would allow for developed streamers in the case of 0.4µs and 1.2µs rise-time impulse breakdown, and bubble formation under 7µs, to be visually confirmed.
- Furthermore, the implementation of a high-speed visual monitoring system would allow for the point of inception of breakdown streamers to be confirmed which would allow for increased accuracy in the derivation of both streamer inception voltage and propagation velocities. Moreover, analysis of streamer velocities making account of statistical and formative time would also increase the accuracy of the calculation of streamer velocities.
- An investigation could be conducted to determine the phenomena responsible for the stark drop in the dielectric strength of the synthetic ester MIDEL 7131 after the first breakdown event when stressed with positive polarity 7µs impulse. This could be done in the first instance by taking measurements of the residual charge remaining within the fluid and test cell after the initial breakdown event.
- Further study of the behaviour of ester fluids and ester-polymer composite insulating systems under impulses shorter than those used in the work discussed in this thesis. While the work conducted in this research programme does represent some impulses generated by pulsed power machines many have output impulses of nominal rise-time <50ns. To ensure that ester dielectric fluids can be used in all pulsed power applications it is important to determine their dielectric performance when stressed with these very short impulses.

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