Effects of Surface Partial Discharges on the Dielectric Strength of Ester Oil-Impregnated Pressboard Insulation in Power Transformers

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Declaration

I declare that this dissertation is my own unaided work. It is being submitted to the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

(Signature of Candidate)

29th . day of **September** year: **2021**.

Abstract

The importance of the smooth operation of power transformers to ensure continuity of supply is indisputable. One of the main transformer failure modes is insulation deterioration because the transformer insulation system constitutes approximately 60% of the transformer material. The aim of the present investigation was to determine the effects of surface partial discharges (also referred to as creepage discharges) on the AC breakdown voltage of ester oil-impregnated pressboard compared to the same effects on mineral oil-impregnated pressboard. This was done by exposing the impregnated pressboard to surface discharges for 0, 3 and 7 hours, followed by subjecting the respective pressboard samples to AC breakdown voltage. The phenomena observed on both the mineral oil and ester oil-impregnated pressboard under exposure to surface discharge activity include bubbles that formed, tree-like white marks propagating from the needle-point to the ground plane and carbon-tracks emanating from the needle point. Some of the mineral oil-impregnated pressboard samples exhibited burn marks as a result of high electric stresses which resulted in further insulator deterioration. The subsequent breakdown voltage results showed a general decline in the breakdown voltage of both the mineral oil and ester fluid cases as the time exposure surface discharges increased from 0 hours to 7 hours. However, the ester oil-impregnated pressboard breakdown voltage values were consistently higher than the mineral oil case by an average of 20%. The observed discharged phenomena and obtained breakdown voltage results are explained using various surface discharge mechanism theories. Exposure of pressboard to surface discharges deteriorates its dielectric strength. The surface discharge mechanisms include insulation deterioration due to cracking, oxidation, high electric field stress and the space charge effect. The present investigation demonstrates how surface discharges affect the breakdown voltage of ester fluid and mineral oil-impregnated pressboard and concludes that ester fluid is a viable possible alternative to mineral oil with regards to the ability to withstand the effects of surface PD on solid insulation in oil filled power transformers.

Dedication

To the one who made me a mom, my first born Kwena:

“Promise me you’ll remember: You are braver than you believe, stronger than you seem, and smarter than you think.”

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This thesis would not have been possible without the assistance and support that I received for which I am thankful.

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I would like to thank Actom for providing the sealed prototype transformer tank and pressboard samples for tests, and the School of Electrical and Information Engineering at the University of the Witwatersrand for the facilities and opportunity to execute this work.

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Lastly, I would like to thank God for making everything possible.

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Glossary of Terms and Abbreviations

Abbreviation/Term	Description
AC	Alternating Current
CDF	Cumulative Distribution Function
DGA	Dissolved Gas Analysis
EO	Ester Oil
FEMM	Finite Element Method Magnetics
FTIR	Fourier Transform Infrared
HV	High Voltage
kV	Kilovolts
MO	Mineral Oil
MVA	Megavolt Amperes
OECD	Organization for Economic Cooperation and Development
PB	Pressboard
PCB	Polychlorinated biphenyl
PD	Partial Discharges
PDF	Probability Density Function
PDPRP	Partial Discharge Phase-Resolved Patterns

Publications:

1. B. Ndlovu and C. Nyamupangedengu, "Effects of Surface Discharges on the Breakdown Voltage of Ester Oil-Impregnated Pressboard Insulation in Power Transformers," 9th CIGRE Southern Africa Regional Conference, Johannesburg, South Africa, 2019, pp. 1-9. See Appendix B for the full paper.
2. B. Ndlovu and C. Nyamupangedengu, "Investigating the Effects of Creepage Discharges on the Breakdown Voltage of Natural Ester Oil Impregnated Pressboard in Power Transformers," 2020 International SAUPEC/RobMech/PRASA Conference, Cape Town, South Africa, 2020, pp. 1-5. See Appendix C for the full paper.

Chapter 1 – Introduction

1.1 Background

Power transformers are arguably the most important and expensive equipment in the electric power transmission network. It is therefore imperative that they are designed, operated correctly and maintained effectively to ensure the continued, reliable functioning of the transformer over its lifetime. The insulation of the transformer forms an integral part in ensuring this continued operation, with an important component being the transformer insulation oil. The function of the transformer oil is to provide cooling as well as insulation function in the transformer.

Evolution of Transformer Insulation Oil Technology

The history and evolution of transformer oil technology began with the use of petroleum-based oils in the late 1800's and has moved toward use and research into the use of vegetable oils in the present time. Figure 1-1 shows an illustration of the timeline of the evolution of oil used in transformers.

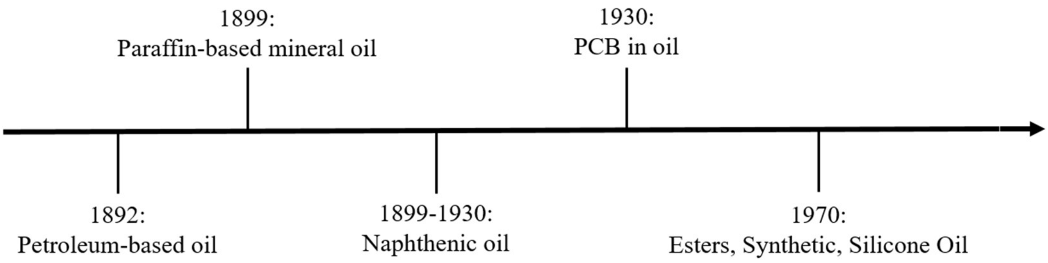


Figure 1-1: Evolution of Transformer Oil Insulation Technology [1]

As shown in the timeline above, the use of petroleum-based oils as a transformer insulation liquid started in 1892. This type of mineral oil was used because of its good aging behaviour, low viscosity, low cost and also that it was readily available [1]. The production of paraffinic-based mineral oil began in 1899. Although this type of mineral oil was an improvement on the petroleum-based oil, it had the following disadvantages: It produces insoluble sludge under certain conditions which lowered the heat transfer capacity through a lowered viscosity and Paraffinic-based mineral oil contained large quantity wax resulting undesirable high pour point [2]. To combat these challenges, paraffinic mineral oil was replaced by naphthenic oils which kept mineral oil as fluid at very low temperature but had the disadvantage of high flammability.

Polychlorinated biphenyl (PCB) oil additives were first made in 1930 which mitigated the flammability of naphthenic oils [3]. However, since the 1970s the public has been increasingly critical of the use of PCB-based transformer oils and it was determined that PCBs were no longer environmentally acceptable, hence the use of PCB was prohibited. With the termination of the PCBs, the power industries turned to other liquid insulation like synthetic esters, vegetable oil, silicon fluid, etc. However, mineral oil remained the major source among these all.

Research into alternatives to mineral insulating oil has been carried out to find out the suitable alternate of transformer oil. Many synthetic, as well as natural organic fluids have been tested and used as an alternative to the transformer oil. Attention has been drawn to vegetable oils like oil from soya beans, sunflower, and synthetic esters as a liquid insulating medium. It is evident in the literature that vegetable oils and synthetic esters have attracted the most attention among all other alternatives of transformer oil [2]. Ester fluids have properties of low flammability, negligible environmental impact, and high moisture tolerance, nontoxic to aquatic life, high flash point, lower volatility and lower pour point. However, the aging of vegetable insulating liquids in the presence of air leads to oxidation resulting an increase of viscosity. Therefore, it is important to take care during filling the insulating liquid in transformers to avoid exposure to atmospheric air (oxygen).

With the introduction of ester fluids to the industry, there is a call for standards to confirm the properties of ester fluid and the possibility of its effective use within a power transformer. This has led to multiple investigations into the performance of ester fluid in comparison to mineral oil. Ester-oil insulation technology is over-taking the mineral oil technology but albeit with challenges that still need to be addressed. One of the challenges is understanding the extent to which exposure to surface (creepage) discharges would compromise the transformer insulation pressboard dielectric strength.

The present dissertation contributes to knowledge with the aim of investigating the effects of surface partial discharges on the breakdown voltage of ester fluid-impregnated pressboard in comparison to mineral oil-impregnated pressboard. The study was conducted by simulating the electrical ageing of pressboard insulation samples through sustained exposure to surface partial discharges. AC breakdown voltage tests were then performed on these samples to determine the effects of using ester fluids (instead of mineral oil) on the ability to withstand breakdown after being subjected to surface PD.

1.2 The Problem Statement

Power transformers are the most important and expensive equipment on the transmission network, making it imperative that they are protected from failure. The most common transformer failure modes are due to lightning and line surges as well as insulation deterioration [4-6]. Since the transformer insulation system takes up about 60% of the entire transformer design, the focus of this research is on transformer failure that is due to the deterioration of insulation.

A major component of the transformer insulation system is the transformer oil. The commonly used transformer oil is mineral oil because of its electrical properties and lower cost. However, failures of mineral oil-filled transformers are catastrophic and affect the surrounding equipment in the substation, personnel and the environment. Ester fluid has thus been introduced as an alternative transformer oil because of its superior fire safety and environmental properties. However, with ester fluids, there is no sufficient knowledge on how they perform and operate within the transformer insulation system and design. Therefore, there is a need for ester fluid standards as there are for mineral oil.

This research project contributes to this knowledge area by investigating the effects of surface partial discharges on the AC breakdown voltage of ester oil-impregnated pressboard in power transformers. This will help in understanding the surface (or creepage) discharge mechanisms occurring within an ester oil-filled power transformer. The knowledge will inform design philosophies of ester-oil insulated power transformers.

1.3 Research Questions

The objective of this research is to investigate the effects of creepage or surface partial discharges on the AC breakdown voltage of ester oil-impregnated pressboard in power transformers and to ultimately find the answers to the following research questions:

- What is the effect of surface partial discharges on the dielectric strength of ester oil-impregnated pressboard insulation?
- How does the increased time of exposure to surface partial discharges (through the electrical ageing of the samples) on the pressboard insulation further impact the breakdown voltage?
- How do the effects of surface partial discharges on the breakdown voltage of ester oil-impregnated pressboard compare and contrast with those on mineral oil-impregnated pressboard?

1.4 Research Hypothesis

Increased exposure of ester oil-impregnated pressboard to surface partial discharges through the electrical ageing process will lead to increased physiochemical degradation of the pressboard insulation. This degradation is expected to result in a decrease in the ability of this solid insulation to withstand electrical stress, which manifests as decreased breakdown voltage. A similar effect is expected to be observed in the mineral oil-impregnated pressboard samples exposed to surface partial discharges under the same conditions. However, ester impregnated pressboard has less degradation due to partial discharge than mineral oil impregnated pressboard when subjected to a similar voltage due to the superior electrical properties of ester fluid. This hypothesis is based on the available knowledge in the literature.

1.5 Dissertation Structure

This dissertation covers the following information laid out in the chapters below.

Chapter 2 – Details the background on the topics that relate to this investigation. This includes a background on common transformer failure modes, the transformer insulation system, properties of mineral oil, ester fluid and pressboard, surface discharge mechanisms and breakdown voltage.

Chapter 3 – Presents an overview of the test specimen preparation.

Chapter 4 – Explains the characterization of the surface partial discharges on oil-impregnated pressboard.

Chapter 5 – Presents the visual observations made during the exposure of pressboard samples to creepage partial discharges.

Chapter 6 – Covers the surface partial discharge induced ageing of the oil-impregnated pressboard.

Chapter 7 – Presents the breakdown voltage results (in different forms) from the abovementioned tests.

Chapter 8 – Presents the breakdown voltage test procedure.

Chapter 9 – Is a discussion and analysis of the observations and results found during this investigation.

Chapter 10 – This chapter concludes the dissertation by highlighting the key findings and conclusions made, as well as the recommendations.

Appendix A – Complete Weibull calculation computation.

Appendix B – CIGRE Conference Paper

Appendix C – SAUPEC Conference Paper

Chapter 2 – Liquid insulation technology in power transformers – a critical review

2.1 Introduction

In order to investigate the effects of surface partial discharges on the AC breakdown voltage of ester oil-impregnated pressboard insulation in power transformers, a brief background is given regarding the transformer failure modes, transformer insulation system, the properties of mineral oil, ester fluids and pressboard insulation. In addition, the surface discharge mechanisms and the effects on insulation are explored. Lastly, a brief explanation of AC breakdown voltage and the factors that influence it is given.

2.2 Transformer Insulation System

In order to reduce transmission losses over long distance lines, AC transmission voltages have been increased to as high as 765 kV on the South African power system and beyond 1 MV elsewhere such as China. As a result of increased voltage stresses, transformer insulation and the related costs are major factors to consider during transformer design [7, 8]. This increase in voltage and power ratings result in enormous physical transformer sizes that push the boundaries on transportation feasibility. It is thus important that better insulation is used to ensure that the transformers can withstand higher electrical stresses in a smaller volume [7-10].

The transformer insulation is an essential part of the transformer. Its main function is to insulate the active parts of the transformer and to ensure safe operation during normal and over-voltages [4]. The most commonly used material to insulate the transformer active parts is oil-impregnated solid insulation in combination with the liquid insulation. The solid insulation in this case is usually pressboard and Kraft paper. Pressboard insulation on its own has internal air voids which reduce the insulation strength and affects the ability to dissipate heat. However, when solid pressboard insulation is impregnated with transformer oil, the internal voids are filled-up with the oil which improves the insulation strength and performance of the pressboard. The combination of pressboard and oil is thus the preferred insulation due to its high electrical strength. A common shortcoming is contamination which is mostly moisture. The following sections detail the properties of these materials (oil and paper) respectively.

2.2.1 Transformer Oil

Transformer oil is an important component of the insulation system which ensures the safe operation of the transformer. Transformer oil has the following functions within a transformer [11,12]:

- **Heat Dissipation or Cooling**: Due to power losses, the active parts (windings and core) of the transformer can get overheated during operation. Heat is taken away from windings to the transformer tank and then to the atmosphere through the process of convection and conduction. Transformer oil facilitates these processes; however, its heat dissipation performance is dependent on the transformer oil's viscosity, thermal conductivity, flash point and pour point.
- **Electrical Insulation**: Transformer oil provides electrical insulation of the active parts of the transformer during operation. In addition, it provides a protective layer that prevents the oxidation of metallic surfaces. Chemical compatibility of the oil with the metallic surfaces and indeed all other functional materials in the power transformer is important.
- **Online Condition Monitoring**: Transformer oil provides a mechanism to determine the conditions of the transformer while it is still in operation. This is done through the technology of Dissolved Gas Analysis (DGA). A sample of the oil is extracted, and the dissolved gasses analysed to determine the transformers' condition and to predict incipient faults that might occur.

A comparison of the heat dissipation and electrical insulation properties are explained in Section 2.2

The properties of an ideal transformer fluid are that it needs to have high dielectric strength, low dissipation factor, low viscosity, high specific heat capacity, high flash point, non-flammable and cost effective [11,12]. The transformer oils considered for this research project are mineral oil, which is currently the most commonly used transformer oil, and natural ester fluid which is the proposed alternative transformer oil. The following sections discuss the properties of mineral and ester fluids respectively.

2.2.2 Mineral Oil

Mineral oil is commonly used as a transformer oil due to its low cost and high availability. It meets the transformer oil requirements mentioned in section 2.2.1 and satisfies the main uses of heat dissipation and electrical insulation within the transformer.

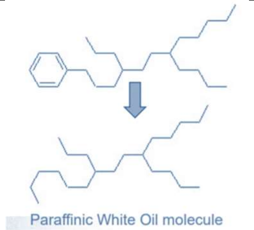
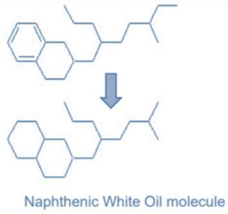
Mineral Oil Composition

Mineral oil is produced by refining petroleum and compromises of various hydrocarbon compounds with specific chemical structures. Mineral oil is therefore not renewable, and this becomes a major shortfall leading to alternatives such as organic oils. Mineral oil is prepared by distilling crude oil which is then separated into different commercial fractions which results in industrial products [1,12]. This then undergoes a number of physical and chemical treatment processes which results in a refined mineral oil product that can be used in transformers.

Mineral Oil Types

The main types of mineral oils used in transformers are Paraffins, Naphthenes and Aromatics. The description and chemical structure of these mineral oil types are shown in Table 2-1. The hydrocarbons shown are proportioned to the respective percentages in accordance with the required composition of the petroleum to be refined. Although mineral oil has well proven good electric properties and is thermally stable, it has its disadvantages.

Table 2-1: Types of Mineral Oil

	Description	Chemical Formula	Typical Chemical Structure
Paraffins	Straight chain hydrocarbons	C_nH_{2n+2}	
Naphthenes	Saturated cyclic hydrocarbons	C_nH_{2n}	
Aromatics	Unsaturated hydrocarbons with ring structure	C_nH_n	

Properties of Mineral Oil

The hydrocarbon composition of mineral oil becomes hazardous to the environment in the case of oil spillage (mineral oil is only biodegraded very slowly). This danger to the environment is greatly increased as the mineral oil ages over time because it contains carcinogenic polycyclic aromatic compounds (such as benzene, toluene and xylene) which triple the damage (or threat index) to the environment [13-15]. This is exhibited by the damage to soil as a result of the spill. Nearby water bodies can be contaminated which has a negative effect on vegetation and possibly any animals in the contaminated space. The consequences of contamination due to hydrocarbons will result in a large amount of undrinkable water in accordance with the condition shown below [13].

1 kg spilled mineral oil → 5 000 000 litres undrinkable water

The harm to the environment is further worsened by the fact that mineral oil has a very low biodegradability factor of 10%, according to the Organization for Economic Cooperation and Development (OECD) 301 standard [16].This means that after 28 days of environment contamination by mineral oil, only 10% of the oil has broken down due to self-degradation due to the action of soil microbes who use it as food.

In addition to the non-biodegradability, mineral oil has a low flash point in class O and is thus combustible [13, 17]. This means that transformer failure (as an example due to a short circuit) will result in catastrophic damage of the transformer and nearby equipment. Moreover, the by-products of this ignition of mineral oil would lead to air pollution. Table 2-2: Properties of Mineral Oil.

Table 2-2: Properties of Mineral Oil

Characteristic	Unit	Value
Biodegradability	%	10
Flash point	°C	150
Fire point	°C	170
Fire Hazard Classification	No units	O
Viscosity at 20 °C	mm^2/s	22
Permittivity at °C	No units	2.2

The abovementioned environmental and safety challenges associated with the use of mineral oil in transformers prompt the use of alternative transformer liquid insulation; ester fluid whose properties are reviewed in the next section.

2.2.3 Ester fluids

Although mineral oil has been the preferred transformer insulating fluid for its good dielectric properties and lower costs, ester fluids are increasingly being implemented as an alternative solution. The main reasons for transitioning to ester fluids are its environmental and operational safety benefits [17].

Ester fluid Composition

Esters are formed through a chemical reaction (esterification) between an alcohol and an acid. The chemical structure of esters is shown in Figure 2-1 below [18].

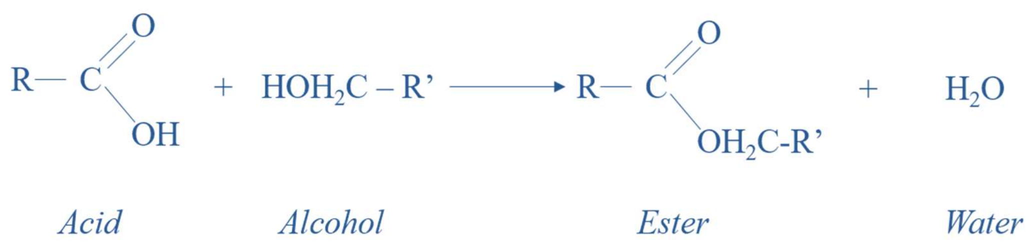


Figure 2-1: Esters Chemical Structure

Types of Ester fluids

There are two main types of ester fluids, namely:

- Natural Ester fluid
- Synthetic Ester fluid

Since natural ester fluids are made primarily from crop seed oils (vegetable oils) such as soya and rapeseed, natural ester fluid can differ based on the different plants that different oils are made from.

Properties of Ester fluids

A comparison between mineral oil and two types of ester fluids is presented in Table 2-3 below [19-24].

Table 2-3: Comparison of Ester Oils vs Mineral Oil

Characteristic	**Unit**	**Mineral Oil**	**Natural Ester fluid**	**Synthetic Ester fluid**
Biodegradability in 28 days	%	10	97	89
Flash point	°C	150	316	260
Fire point	°C	170	360	316
Fire Hazard Classification	-	O	K2	K3
Viscosity at 20 °C	mm^2/s	22	85	70
Permittivity at 20 °C	-	2.2	3.3	3.2

As is shown in Table 2-3, one advantage of using ester fluids is that they are biodegradable with a biodegradability factor as high as 97. This means that in 28 days of exposure to the environment, 97% of natural ester fluid would have succumbed to self-degradation. According to the OECD 301 standard [16], a substance is considered biodegradable if it can decay to above 60% within the first 28 days [13, 16], therefore according to Table 2-3, both synthetic and natural ester fluids are readily biodegradable. This property makes ester fluids nontoxic to the environment. One of the disadvantages is that natural ester fluids are prone to oxidation which is why they can only be used in sealed applications.. This is however counteracted by applying low concentrations of oxidation inhibitor packages which help slow down the oxidation process [19].

Ester fluids have good fire safety properties which are demonstrated by the high flash and fire points of 316 °C and 360 °C, according to ISO 2719 and ISO 2592 respectively [17, 19]. Since these ester fluids have a fire point that is greater than 300 °C, they are classified in the IEC 61100 standard, as K fire hazard class dielectric insulating fluids. These improved safety factors mean ester fluids will not sustain a flame in the absence of a high-energy ignition source. Such a property is especially advantageous since the required electrical clearances between pieces of high voltage equipment become reduced and fire mitigation systems costs are lessened. Esters are extremely hard to ignite due to their high fire point, whereas, burning mineral oil gives off a dense black smoke, which is harmful if inhaled, hence the importance of nontoxic property of ester fluids.

The use of ester fluids enhances performance capabilities by extending the life span of cellulose-based solid insulation (paper and pressboard). The water solubility of ester fluids is up to 50 times greater than that of mineral oil at ambient temperature [19]. Since cellulose-based solid insulation is hygroscopic it tends to absorb moisture from the environment. Therefore it is an advantage that natural esters are hygroscopic, thus drawing moisture out of the solid insulation and absorbing it, hence keeping the insulation dry and extending the life span of both the solid insulation and the power transformer.The presence of moisture reduces the dielectric strength of the insulating oil because the moisture will break down the molecular chains of the insulating oil, making the oil more conductive [25].

One disadvantage of using ester fluids is the higher viscosity when compared to mineral oil. This affects the heat transfer capabilities in the transformer. The higher viscosity of esters compared to mineral oil is well known but easily allowed for in ester transformer designs. Given the rapid increase in the use of esters, the industry sees that the advantages of esters outweigh minor disadvantages. In addition, the use of ester fluids requires special impregnation processes, and they are more expensive than mineral oils.

2.2.4 Transformer Solid Insulation – Pressboard

The most commonly used solid insulation in power transformers is pressboard. This insulation material does not electrically deteriorate as long as the material retains its mechanical strength [26]. Pressboard provides good dielectric properties which are further enhanced through the process of oil impregnation. It is thus used in high voltage applications in power transformers to resist the physical and electrical stresses experienced by the transformer windings and core.

Pressboard insulation provides more than the mechanical separation between the active parts of a transformer, its dielectric properties improve the insulation properties of the entire transformer insulation system. Pressboard is made of multiple compressed layers which have good insulating properties in the form of a high dielectric constant.

The disadvantage of using pressboard insulation is that it is sensitive to moisture. Moisture may be trapped in between the stacked compressed layers. Moisture may also develop due to the normal ageing of the oil-paper insulation system [26, 27]. The presence of moisture in the solid insulation increases dielectric losses and therefore decreases the dielectric strength of the pressboard insulation.

Pressboard Chemical Properties

Pressboard is made of cellulose which comes from plants. Cellulose is a linear polymer of glucose elements. The chemical structure of cellulose is shown in Figure 2-2.

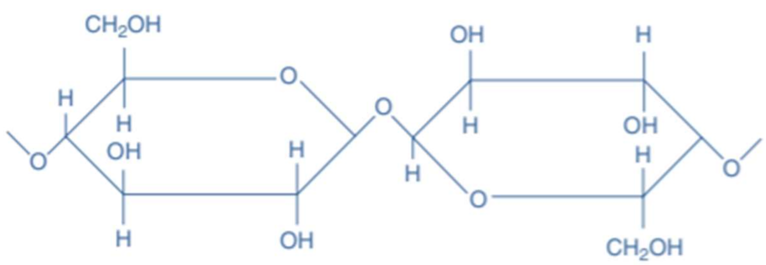


Figure 2-2: Cellulose Chemical Structure

Types of Pressboard

There are four types of pressboard which are discussed below. The various types differ in the manufacturing process.

- Calendared Pressboard:

The manufacturing process of calendared pressboard commences with a pressing operation which results in pressboard with 55% moisture content. The pressboard then undergoes a drying process subjected to heat without pressure which results in a 5% moisture content pressboard and density that ranges between 0.9 and 1.0 g/cm3. Finally, the samples undergo further compression under heavy rollers which increase the density to between 1.15 and 1.3 g/cm3.

- Moldable Pressboard:

The main difference in the manufacturing process of moldable pressboard is that it does not under extensive pressing after the manufacturing process. The samples are dried to a moisture content of approximately 5% and density of 0.9 g/cm3. This results in soft pressboard that has good oil absorption properties and can be shaped, to a certain degree, to meet the required physical requirements.

- Pre-compressed Pressboard

This pressboard type undergoes a pre-conditioning process which includes dehydration, followed by compression and finally a drying process directly from the wet stage in the manufacturing process. The bonding fibers thus produce a stable, stress-free and strong pressboard material with a density of approximately 1.25 g/cm3. Due to these characteristics, pre-compressed pressboard is the most commonly used solid insulation in transformers. Additionally, this pressboard type maintains its shape throughout the entire transformer manufacturing process as well as during thermal cycling of oil during maintenance procedures [26].

▪ Laminated Pressboard:

The manufacturing process of laminated pressboard can be either one of the abovementioned pressboard types, however as a final step, the pressboard is laminated. This pressboard type can be manufactured to thickness between 10 mm and 50 mm and is mostly used for winding support platforms and end support blocks and cleats for securing and supporting leads.

2.3 Transformer Failure Modes

The most common transformer failure modes are due to lightning and line surges and insulation deterioration as shown in Figure 2-3. Since the transformer insulation system makes up 60% of the transformer, the focus of the present research is on transformer failure that is due to insulation deterioration. This deterioration may result in insulation breakdown due to increased electric field stress. The insulation failure results in the bridging of the insulation region thus bridging the potential difference between the HV and ground electrodes. Surface discharges are among the agents of ageing and failure in power transformers.

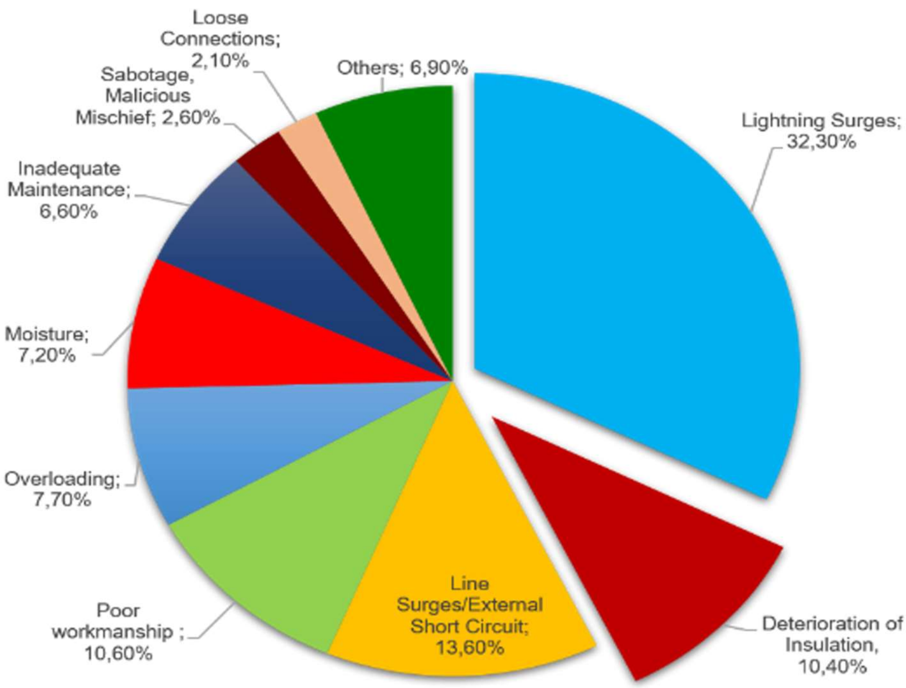


Figure 2-3: Common Transformer Failure Modes [4]

2.4 Surface Discharge Mechanisms

Partial discharges are one of the major factors that lead to dielectric failure of power transformers. Consequently, power outages occur as a result. It is therefore important to prevent or minimize the occurrence and development of partial discharges in the transformer.

Partial discharges occur in the insulation system of the transformer (that is, the transformer oil and the solid pressboard insulation). The main cause of partial discharges is air bubbles in the insulation. Partial discharges accelerate the deterioration of the insulation system, thus decreasing the dielectric properties and consequently the time of use of the insulation and the power transformer. In addition, power transformers are exposed to electrical, thermal, mechanical, and environmental stresses. These are due to high voltage, frequency, electrical currents causing thermal stress, vibrations causing mechanical stress and moisture and contamination from exposure to environmental conditions [49].

These stresses in the transformer, together with possible impurities in the material or imperfections in the manufacturing process can cause the components of the transformer insulation system to have air bubbles that contribute to the decrease in their insulation capabilities. This insulation deterioration can be in the form of partial discharges which could occur at the interface between the solid and liquid insulation (transformer oil and pressboard) due to the influence of high electrical stresses [28- 34]. In power transformers this type of surface partial discharges are commonly referred to as creepage discharges.

Surface discharges are initiated and propagated when there is a high electric field along the surface of solid insulation. The possibility of surface partial discharges occurring increases at an interface between insulation materials with different permittivities. Therefore, the mechanisms with which surface partial discharges propagate are dependent on the properties of both insulation materials at the interface. In this case, surface discharges occurring at a pressboard-mineral oil interface could be generated and propagated through different mechanisms when compared to surface partial discharges occurring at a pressboard-ester fluid interface. This is the key motivation for the present work. Furthermore, the surface partial discharge mechanisms are affected by the charge distribution in the system as well as the applied voltage waveform and polarity.

Transformer design approaches are used to prescribe suitable safety clearances between conductors and insulators within a transformer. Clearances are determined by predicting the possible electric field stresses occurring within the transformer under different operating conditions. However, the presence of surface charge will alter the behaviour of the insulation system. Even if the initial charge distribution is known, a discharge moving across the surface changes the distribution of capacitances thereby modifying the electric fields in the system. Trapping of static charge on solid insulation surfaces due to friction with ester fluids is a phenomenon of concern and therefore possible area of research. In the present work however, it is assumed that there is no static charge influence. The present work focuses on creepage discharge effect on dielectric strength (breakdown voltage) of oil-impregnated pressboard in ester fluids compared to in mineral oils.

2.5 Breakdown Voltage of Insulation

The transformer insulation system plays a vital role in ensuring the continued operation of the transformer by insulating the conductors of the transformer. It is therefore imperative that the insulation is kept in the best condition to avoid transformer failures. One of the most important properties of insulation material is the breakdown voltage. The breakdown voltage of an insulation material is the voltage at which the insulation is unable to resist the flow of current through it. Electrical breakdown occurs when the applied electric field stress exceeds the dielectric strength of the insulation, making it conductive. The voltage at which breakdown occurs is known as the breakdown voltage. Determining the dielectric breakdown voltage of an insulation material is important to understand the insulation's ability to withstand electric stress without failure.

The presence of partial discharges may reduce the quality of the insulation system and thus the ability to withstand breakdown and this is the objective of the present research with the experiment methodology explained in the next chapter.

2.6 Conclusion

This chapter presented the transformer insulation system and explained the properties of mineral oil, ester fluid and pressboard insulation. The insulation is important in preventing transformer failures, therefore the surface discharge mechanisms that could compromise the insulation were discussed. The breakdown voltage which is used as a measure of the quality of the insulation was explained. In the next chapter, the experiment methodology with respect to test specimen preparation is presented.

Chapter 3 – Experimental Setup and Characterisation of Surface Partial Discharges

3.1 The Experimental Work: Tests Specimen Preparation

In order to study the effects of creepage discharges on the AC dielectric strength of ester fluid-impregnated pressboard, the experimental work comprised of three main phases. Firstly, the pressboard test specimens had to be prepared. Secondly the test specimens were then exposed to sustained creepage partial discharges. Finally, breakdown voltage tests were conducted on the test specimens. The complete experimental process is illustrated in Figure 3-1. The preparation of the pressboard samples is presented next in this chapter. The other two phases of the experimental work are presented in separate chapters.

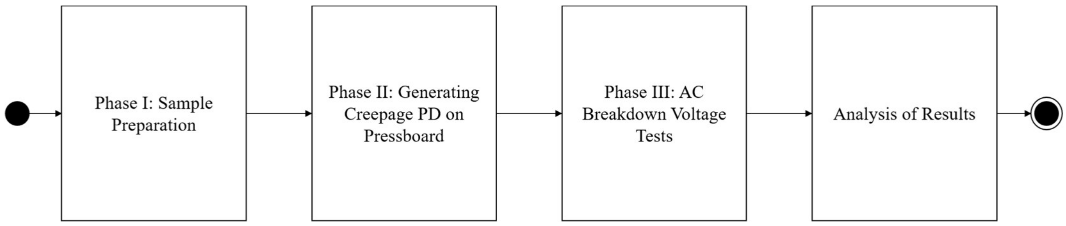


Figure 3-1: Experiment Methodology Flow Diagram

3.1.1 Oil-impregnated pressboard test specimen preparation

The sample procurement stage consists of acquiring both the oil and pressboard samples as well as the preconditioning of the latter. The purpose of the investigation is to compare the influence that creepage partial discharges have on pressboard impregnated with two transformer oil types. The oil samples that were procured and used were mineral oil, and canola-based natural ester fluid. Tests were done in mineral oil to compare with ester fluid results obtained under the same conditions.

The ester fluid was provided for by M & I Materials. The properties of the transformer oils at room temperature are shown in Table 3-1 [14-17].

Table 3-1: Transformer Oil Properties

	Standardized Method	Mineral Oil	Canola-based Natural Ester fluid	Soy-based Natural Ester fluid	Synthetic Ester fluid
Density @ 20 °C g/cm^3	ISO 3675	0.888	0.92	0.92	0.97
Viscosity @ 40 °C, mm^2/s	IEC 296	11	37	32	29
Viscosity @ 0 °C, mm^2/s	IEC 296	1800	232	206	1440
Flash Point, °C	ISO 2719	> 140	> 315	> 315	260
Pour Point, °C	ISO 3016	-45	-31	-18	-56
Water Content, mg/kg	IEC 296	30	50	50	50
Acidity post the IEC 61125 test	IEC 1125	1.2	< 0.1	< 0.07	0.02

Pre-compressed pressboard samples that were of dimensions 90 mm x 90 mm x 3 mm were procured to be used in the experiments. In order to achieve a controlled experiment, the pressboard samples underwent the standard appropriate preconditioning process [35]. This is done to ensure carefully controlled moisture levels and the degree of oil-impregnation of each pressboard sample. The IEC 60554-2 standard is used to define the process with which pressboard samples are manufactured and impregnated with new (unused) transformer oil.

The complete preconditioning process that was followed in the manufacturing of the pressboard samples is shown in the flow diagram in Figure 3-2.

The main aim of the process shown in Figure 3-2 is to remove moisture and gasses from the fibrous cellulose pressboard structure and refill the interstices with oil molecules, thus extending the life of the pressboard as an insulator [35]. After the impregnation processes, the oil-pressboard insulation medium forms a composite insulation structure with the oil.

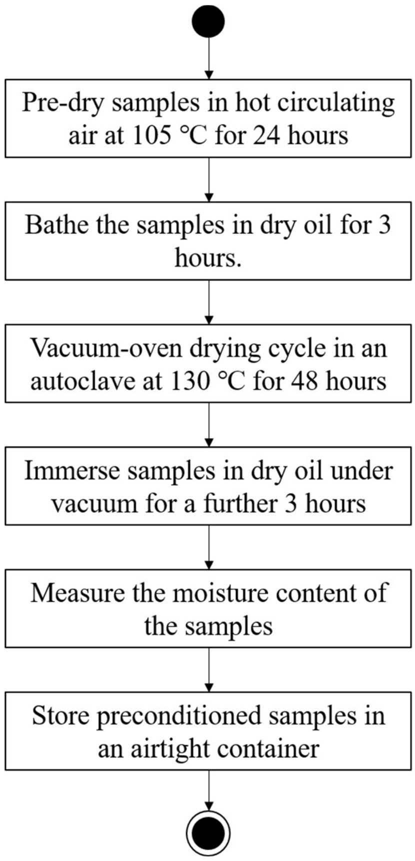


Figure 3-2: Pressboard Preconditioning Process in Accordance with IEC 60554-2 [35]

The abovementioned pressboard preconditioning and cutting processes were done at a power transformer manufacturing company (Actom Pty Ltd.) as part of their manufacturing process in Germiston, South Africa. To ensure that the test samples were not exposed to atmospheric air and moisture during transportation to the laboratory and storage prior to experimentation, they were immersed in the respective oils and kept in airtight containers as shown in Figure 3-3. The samples would be ready for electrical ageing under sustained creepage discharges as presented in the next section.

Figure 3-3: Oil Impregnated Pressboard Samples in Airtight Containers

3.1.2 Conclusion

The present section discusses the sample procurement and preparation process. The transformer oils were procured and kept in sealed containers. The pressboard preconditioning process was carried out in accordance with IEC 60554-2 at a power transformer manufacturing company. The pressboard test specimen were immersed in their respective transformer oil and stored in air tight containers to prevent exposure to atmospheric air and ready for the next phase of the investigation.

3.2 Setup Used for the Characterization of Surface Partial Discharges on Oil-Impregnated Pressboard

Surface discharges in power transformers occur due to enhanced electric field on the interface between the oil and pressboard insulation. The stress enhancement is initiated by various factors such as geometry of different material interfaces as well as elevated voltages on the electrodes [28, 34]. In order to conduct the study of surface discharge effects on the dielectric strength of oil-impregnated pressboard, firstly the test cell had to be designed, the surface discharges characterized, the ageing process conducted and then the electrical breakdown tests conducted. This chapter is on the design of the test cell followed by the characterization of the surface discharges on the pressboard specimen.

3.2.1 Experimental Setup for Surface Discharge Characterization on the Oil-Impregnated Pressboards in Ester fluid and in Mineral oil

The electrical circuit used in generating and characterizing the surface discharges formed on the pressboard is illustrated in Figure 3-4 below.

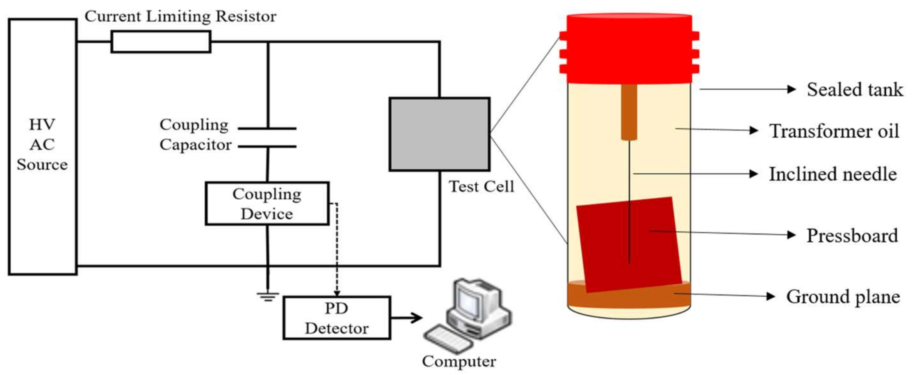


Figure 3-4:Experiment setup for the characterization of surface PD on oil-impregnated pressboard

The test circuit shows how the surface discharges are formed and measured. The test object shown in Figure 3-4 is the electrode configuration that promotes surface PD generation. The current limiting resistor is placed between the source and the test object for the main function of limiting fault current flow in case of a flashover in the test specimen and the coupling capacitor decouples the PD measurements and converts them to voltage pulses that can be analyzed.

There are three main methods used in creating surface discharges for experimental studies in the laboratory: the point-plane, parallel plane-plane and needle-plane methods. The methods are explained in the next section including criteria used in selecting the methods used in the present work.

3.2.2 Design of the Electrode Configuration for Surface PD Generation in the test cell

Point-plane method of surface discharge creation

This method is used to promote surface discharge on insulation material. The experiment setup is as shown in Figure 3-5 below.

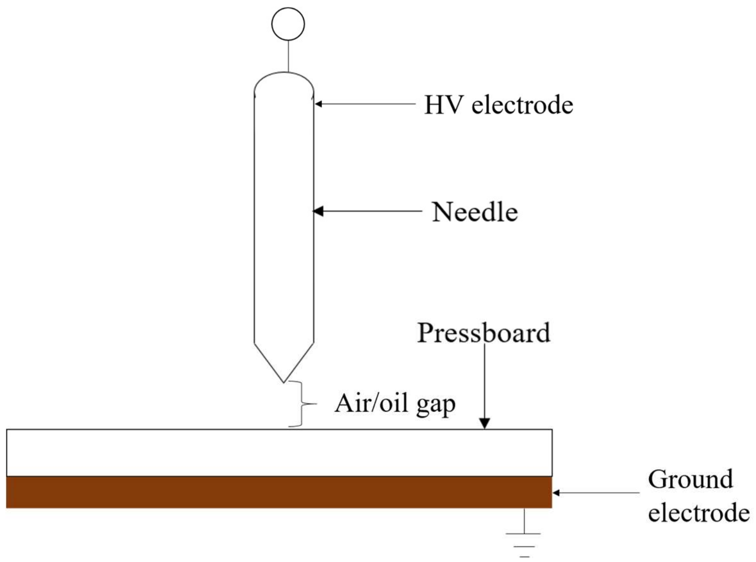


Figure 3-5: Point-Plane Electrode Configuration

When high voltage is applied onto the needle, the electric stress intensifies at the needle tip. This results in radial discharges around the tip, which then lead to tracking patterns on the pressboard surface [28]. It has been found that the problem with this method is that although partial discharges may occur on the surface of the pressboard, the surface discharges cannot be reliably generated and sustained because the needle produces an intense and directional electric field which usually leads to a relatively quick electrical puncture through the bulk of the pressboard insulation. This method was therefore not adopted in the present work.

Parallel plane-plane method of surface discharge creation

The electrode setup for the parallel planes method is illustrated in Figure 3-6. In this arrangement, parallel plane electrodes are separated by a perpendicular pressboard and on one of the planes; a small point source is attached. This method generates surface discharges, however it is difficult to distinguish the general field from the localized electric field [28].

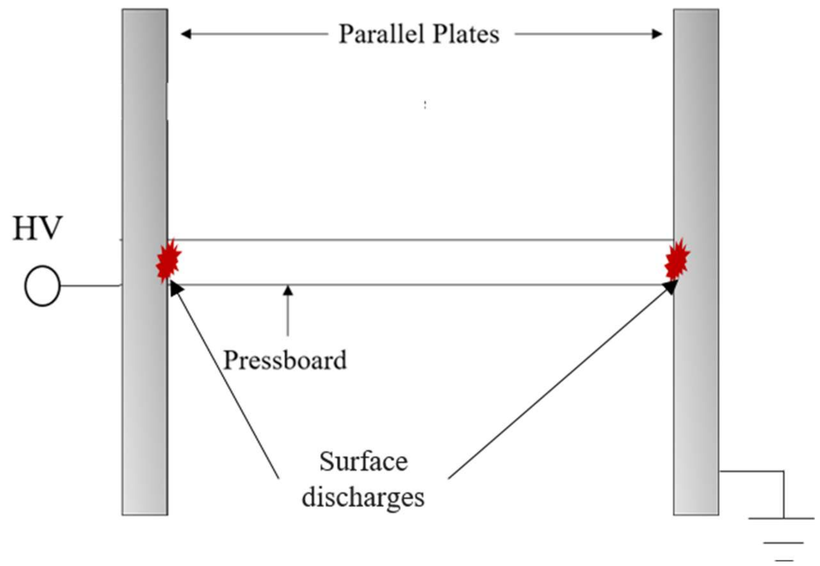


Figure 3-6: Parallel planes experiment setup

Chosen Method: Needle-plane method of generating surface discharges

The abovementioned methods do not comply with BBS EN60112:2003 standard for measuring the comparative tracking index for solid insulation where the discharge source and earth are on the same side [28]. The correct method is the needle-plane which is shown in Figure 3-7 and Figure 3-8 below.

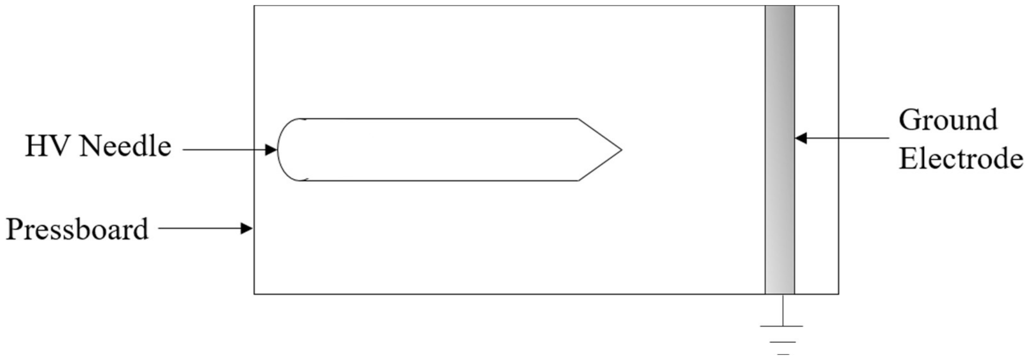


Figure 3-7: Needle-plane experiment setup (Top View)

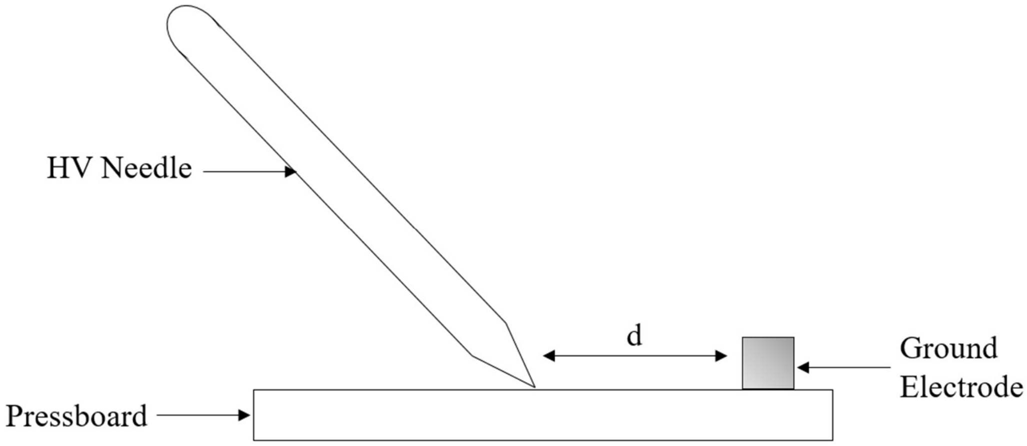


Figure 3-8: Needle-plane experiment setup (side view)

The needle at high voltage is placed at an acute angle on the pressboard at a distance ***d*** from the earthed electrode, which is also placed on the pressboard surface. This method has been found to generate sustainable surface discharges for a sufficient duration to allow for the accelerated ageing of pressboard samples with surface discharges [28]. The positive aspects of this method are that the acute angle ensures that a strong tangential electric field component is generated, thus minimizing the vertical component which would lead to premature electrical damage through the pressboard [28, 29].

Initially, simulations were done to determine the optimal gap distance between the HV needle and the ground electrode along the pressboard surface.

3.2.3 Simulations of Surface PD Propagation

The simulation of surface partial discharges is aimed at determining the optimal gap distance ***d*** between the HV needle tip and the earth electrode and the test supply voltage value above the PD inception voltage. The gap distance and supply voltage must allow for a sustained surface discharge for hours without flashover in oil or through the pressboard test sample

With reference to Figure 3-8 the optimal distance ***d*** that ensures that surface discharges are generated on the pressboard, without causing flashover from the high voltage to the ground electrode is determined through FEMM simulations by varying the distance and supply voltage. A distance of 25 mm and voltage of 30 kV was decided upon as shown in Figure 3-9. This gap distance and supply voltage were found to allow for a sustained surface discharge for hours without flashover in oil or through the pressboard test sample, thus successfully generating surface partial discharges correctly for these experimental tests. The electric field stress was higher at the needle tip and decreases when moving towards the ground plane. This proved that the surface discharges could be generated on the surface of the pressboard without causing a puncture through it. It was also noted that there was significantly less electric field stress in the surrounding transformer oil. The time-behavior of the resultant creepage discharges were monitored as explained in the next chapter.

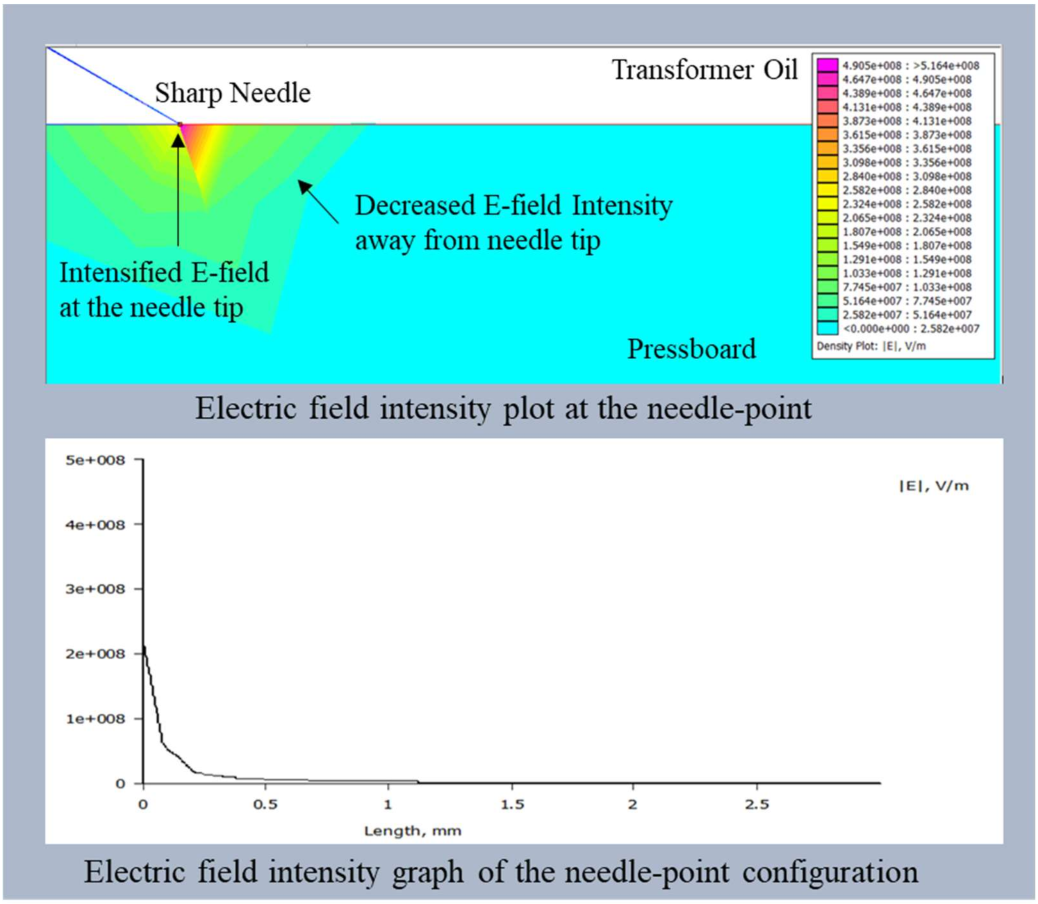


Figure 3-9: FEMM Simulation of surface PD at distance 25 mm from the ground plane

3.2.4 Conclusion

The experiment setup used to generate and characterize the surface partial discharges generated on the oil-impregnated pressboard has been discussed. The acute angle needle-point configuration was chosen, and the parameters used are a distance of 25 mm and 30 kV. The observations and analysis of surface partial discharge characterization are presented in the next chapter.

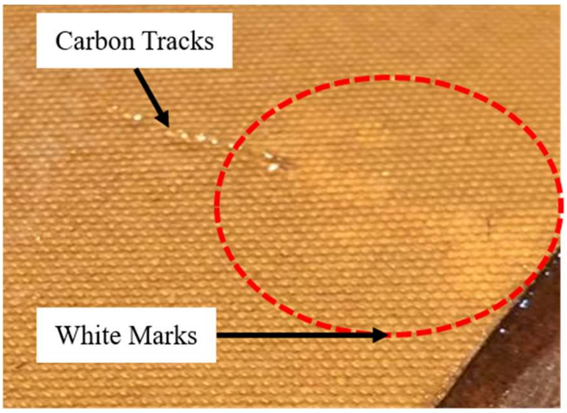
3.3 Characterization of the Creepage Discharge on the Pressboard Specimens

Creepage discharges were generated on the surface of pressboard samples using the process outlined in experiment methodology in the previous chapter. The creepage discharges that formed during this process were similar to those described in literature [36,37] as presented in this chapter.

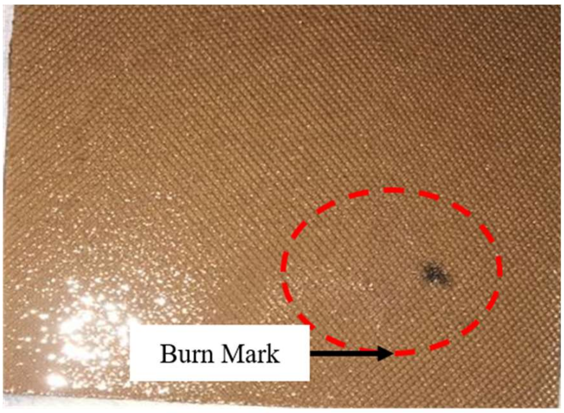
3.3.1 The observed characteristic behaviour of surface discharges on the pressboard samples

The distinct feature associated with surface discharges on pressboard is the initial formation of tree-shaped white marks radiating from the needle point towards the ground plane. The white marks were observed after 30 minutes of voltage application in the ageing process for ester oil-impregnated pressboard and at 45 minutes for mineral oil-impregnated pressboard. Figure 3-10 shows the observed formation of white marks from the needle point in mineral oil and in natural ester fluid and the burn marks that appeared on the mineral oil impregnated pressboard. These white marks manifest the drying up of the pressboard in the region bounded by the HV needle and the ground plane. This is an indication of moisture evaporating from the creepage tracks due to heat on the pressboard. Since white marks are formed due to the drying of the pressboard, they appear earlier in ester fluid pressboard samples because esters are hygroscopic and tend to draw moisture out of the pressboard, however the white marks progress much slower than mineral oil.

The recurrence of surface discharges develop along the path of the white marks forming carbon tracks extending from the needle point as shown in Figure 3-10. The carbon tracks are an indication of further degradation of the pressboard insulation. The hydrocarbon chains breakdown due to energy from the discharge activity leaving behind carbon.



Ester Oil



Mineral Oil

Figure 3-10: Observations on Pressboard Sample in ester and mineral oil

Similar observations were made on both ester oil-impregnated pressboard and mineral oil-impregnated pressboard with the exception of burn marks that appeared only on the mineral oil impregnated pressboard. These marks are an indication of high electrical stress occurring at the needle tip. In addition, the white marks that were observed on the mineral oil-impregnated pressboard were more prominent (and longer) than the ester oil-impregnated pressboard due to the differences in moisture retention. This is because ester fluid molecules hold on to moisture molecules with stronger forces than mineral oil.

The creepage discharge ageing effects manifested as white marks and carbon tracks developing on the pressboard surface progress slower in the ester fluid environment. This is an indication that ester oil-impregnated pressboard could be more resilient to creepage discharge degradation. In addition to visual observations of the creepage discharges, simultaneously, PD measurements were continuously recorded as the discharge activity progressed. The obtained PD signals are presented in the next section.

3.3.2 Phase Resolved Partial Discharge Patterns (PRPDP)

A PRPD pattern is a visual representation of partial discharge activity relative to the 360 degrees of an AC voltage cycle. The partial discharge activity in this case is due to the surface tracking caused by the enhanced electric stress around the needle point on the pressboard surface. The correlation between the observed creepage discharges and the partial discharge phase-resolved patterns (PDPRP) provides the differential information about the creepage discharge mechanisms in mineral and in ester oil impregnated pressboards. The patterns below were obtained over a 30 second period.

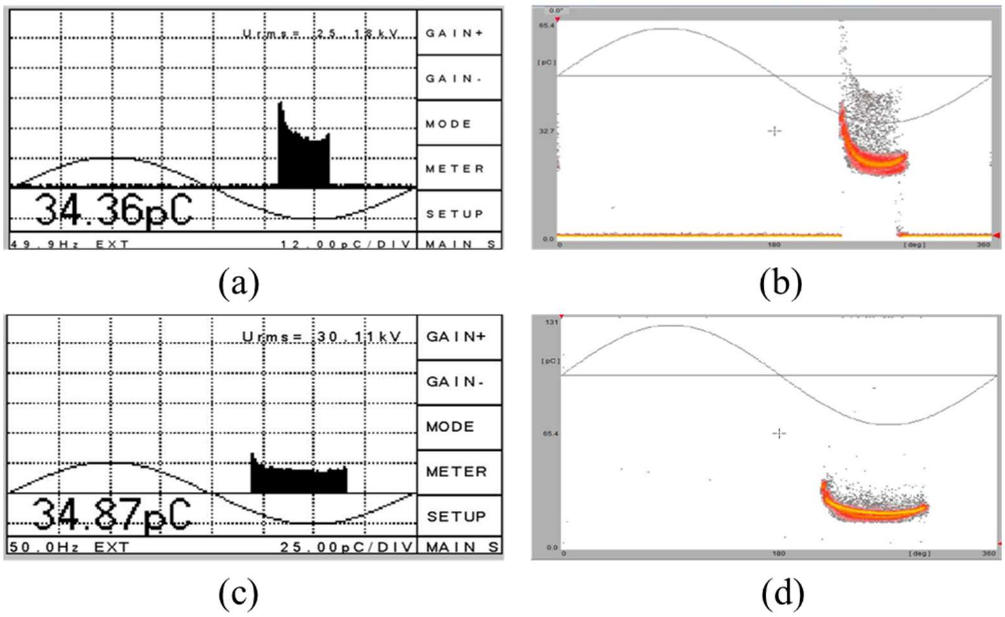


Figure 3-11: PRPDP of (a, b) Ester oil and (c, d) Mineral Oil-impregnated Pressboard at inception

The first PDPRP plot (Figure 3-11) indicates that the general shape is similar and PD pulses occur in the negative half cycle of the AC voltage. This suggests similar surface tracking mechanisms despite the differences in the oil properties.

Furthermore, the partial discharge patterns that occur at inception for mineral and ester fluid respectively are corona-like. The partial discharge activity occurring in the third quarter of the AC voltage cycle indicates the presence of corona activity, around the needle point [36,37].

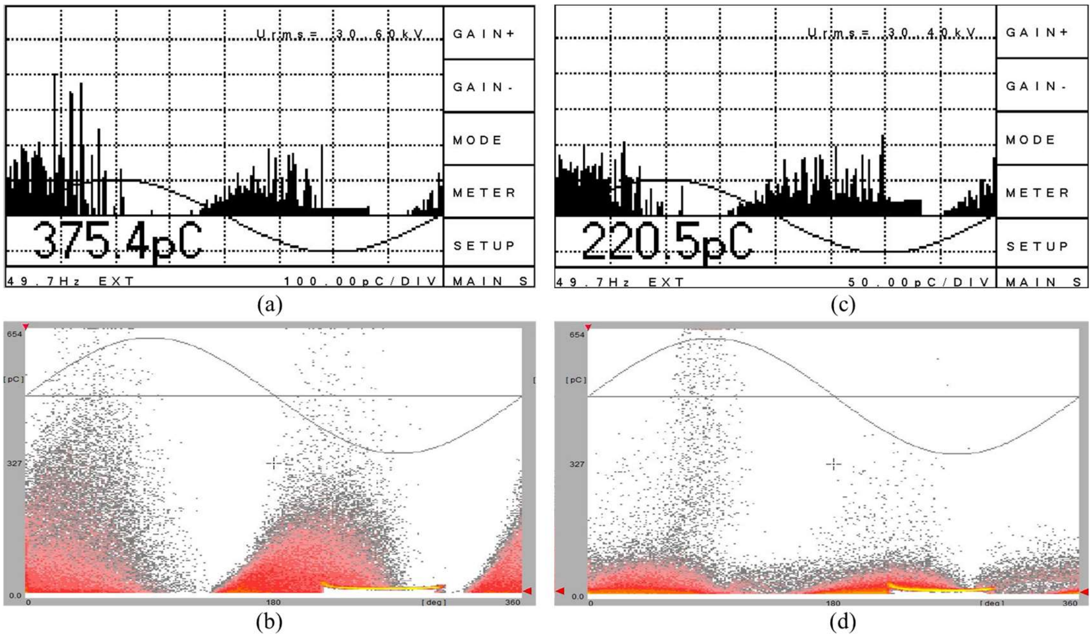


Figure 3-12: PD patterns in ester (a, b) and mineral (c, d) oil after 30 minutes of the same continuous voltage application

After a 30-minute period (for ester oil-impregnated pressboard and 45-minute period for mineral oil-impregnated pressboard samples) where the propagation of white marks begins to form, the partial discharge pattern changes (from predominately occurring in the negative AC voltage cycle) as shown in the third PDPRP plot. With the voltages being the same for both mineral and ester oil, partial discharge activities are widely spread across both the negative and positive half cycles. There is a significantly high intensity of partial discharge activity occurring covering the entire AC cycle [36,37]. Discharges are no longer occurring around the needle tip but on the carbon tracks from the needle tip.

The ageing process results in the appearance of white marks and bubbles. The presence of more intense partial discharge activity on the negative half cycle is more significant in esters than in mineral oil because of the appearance of larger negative discharges under lower voltage levels. The most possible reasons for this would be the influence of hetero charges [38] and residual bubbles left by discharges on the subsequent ones. In addition, since white marks appear due to the drying of the pressboard, they appear earlier in ester fluid pressboard samples because esters are hygroscopic and tend to draw moisture out of the pressboard.

The streamer channels propagating along the pressboard deposit residual charges on the pressboard surface. The hetero charges could increase the local electric field in the next half cycle and promote the development of subsequent streamer of opposite polarity. Mineral oil has lower viscosity than esters; therefore the dispersion of bubbles in mineral oil becomes easier. In esters, with higher viscosities, it is more difficult for the bubbles to disperse freely from the pressboard surface; hence the negative discharges are facilitated. This explains how partial discharge activity appeared to be more in ester oil-impregnated pressboard samples. Regardless, this did not translate into a lower breakdown voltage for ester fluid samples as is shown in later chapters. A more detailed analysis of the surface discharge mechanisms is presented in Chapter 5 .

During the phase of the formation of white marks, space charges increase, thus increasing the conductivity of the surface which temporarily changes the field distribution in the area.

3.3.3 Conclusion

White marks, bubbles and carbon tracking were observed on both the ester oil-impregnated pressboard and the mineral oil-impregnated pressboard as an indication of pressboard deterioration. The white marks appeared earlier in the ester fluid environment due to the drying of the pressboard, however, they progressed more slowly. Differences occurred in the phase resolved PD patterns in the aged phase. The observations made are similar for both oil type with differences that are caused by the different oil properties. The similarities however suggest similar surface discharge mechanisms occurring in both ester fluid and mineral oil. A detailed analysis on the surface discharge mechanisms are presented in Chapter 5 The procedure followed in simultaneous ageing of multiple pressboard samples is presented in the following chapter.

3.4 Surface Discharge Induced Ageing of the Multi-sample Oil-Impregnated Pressboard – Setup and Procedure

The process of electrically ageing pressboard is done by generating surface discharges. In the present work, in order to investigate the effects of surface discharges on the breakdown voltage, the pressboard samples were exposed to creepage discharges for varying durations. The sample categories were un-aged, aged for 3 hours and aged for 7 hours for both ester fluid and mineral oil impregnated pressboard samples. This chapter details the experimental setup and procedure used to expose multiple pressboard samples to surface partial discharges for the respective time.

3.4.1 Experimental Setup Parameters

The details of test samples that were exposed to surface partial discharges are listed in Table 3-2 below. The sample sets shown in Table 3-2 contain six oil-impregnated pressboard samples each. There are three sample sets for each oil type (ester fluid and mineral oil) which were aged for 3 hours and 7 hours. The first sample set contains unaged pressboard samples for both oil types for control tests. There are therefore, six sample sets containing 6 oil-impregnated pressboard samples, giving a total of 36 pressboard samples to be tested.

Table 3-2: Pressboard samples test duration details

Sample Set	1	2	3
Oil Type	**Time of Exposure (hours) to Surface PD**		
Mineral Oil	0	3	7
Canola-Based Natural Ester fluid	0	3	7

3.4.2 Experimental Setup for Ageing of Pressboard Sample Sets

A set containing 6 samples each of dimensions 90 x 90 mm oil-impregnated pressboard samples allows for pressboard samples to be aged simultaneously for the required amount of time.Figure 3-13 shows the 6 needle-point electrode configurations and how they were set up in the tank.

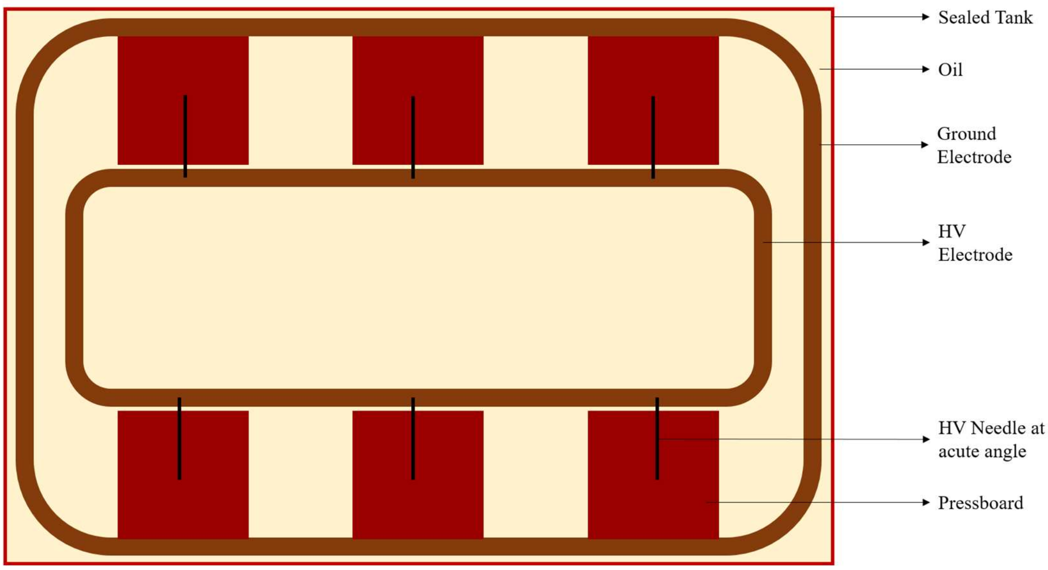


Figure 3-13:Top view of 6 needle-point electrode configuration sample set schematic in a sealed oil-filled tank

To avoid moisture ingress and contamination during the execution of the experiment, a sealed tank is used as shown in Figure 3-14. The array of pressboard samples in a sample set are placed in a sealed tank filled with the respective oil under test. The tank is filled with oil to avoid sporadic arc flashes that could occur in different parts of the tank. The oil plug shown in Figure 3-14 is the breathing facility during oil filling.

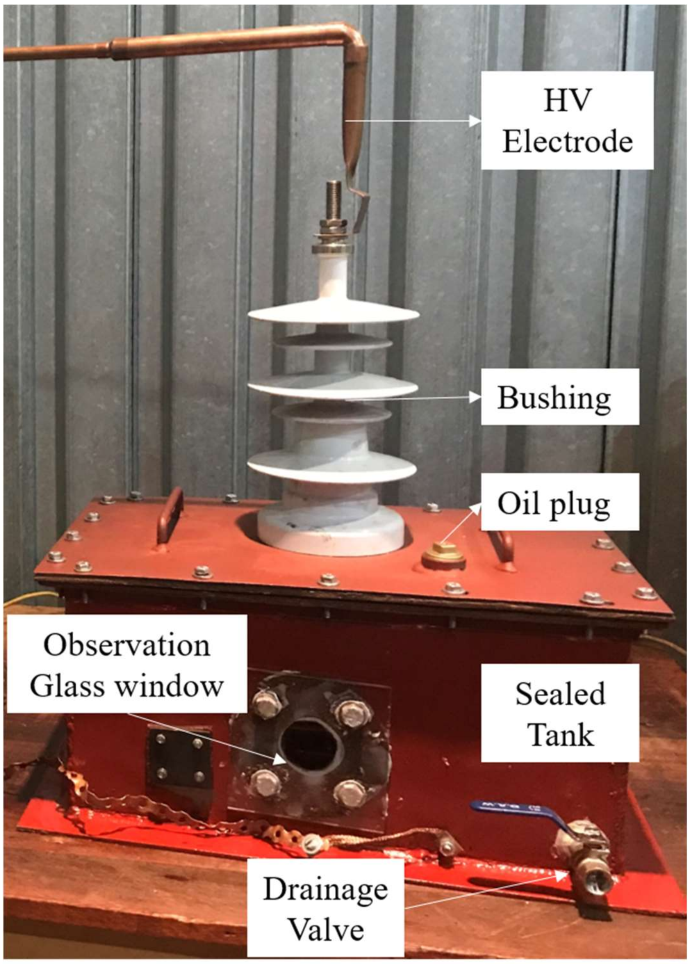


Figure 3-14: A picture of the sealed tank used for the multiple sample ageing experiments

The sealed tank filled with oil and the pressboard sample set properly secured inside the tank is connected to an AC voltage source as shown in Figure 3-15 and Figure 3-16. The samples are then aged for the required time (3 or 7 hours).

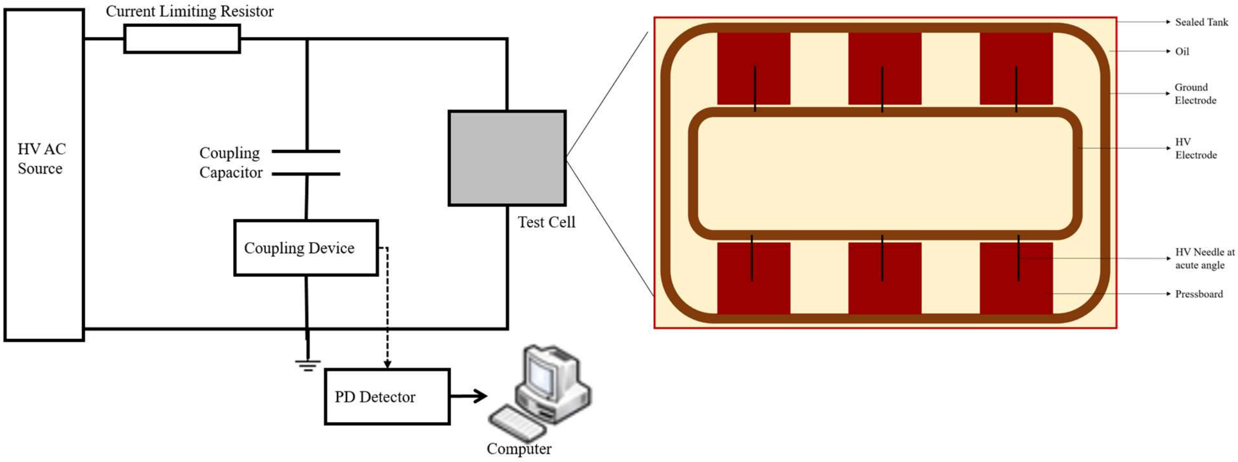


Figure 3-15:Electrical setup for ageing of multiple pressboard sample sets

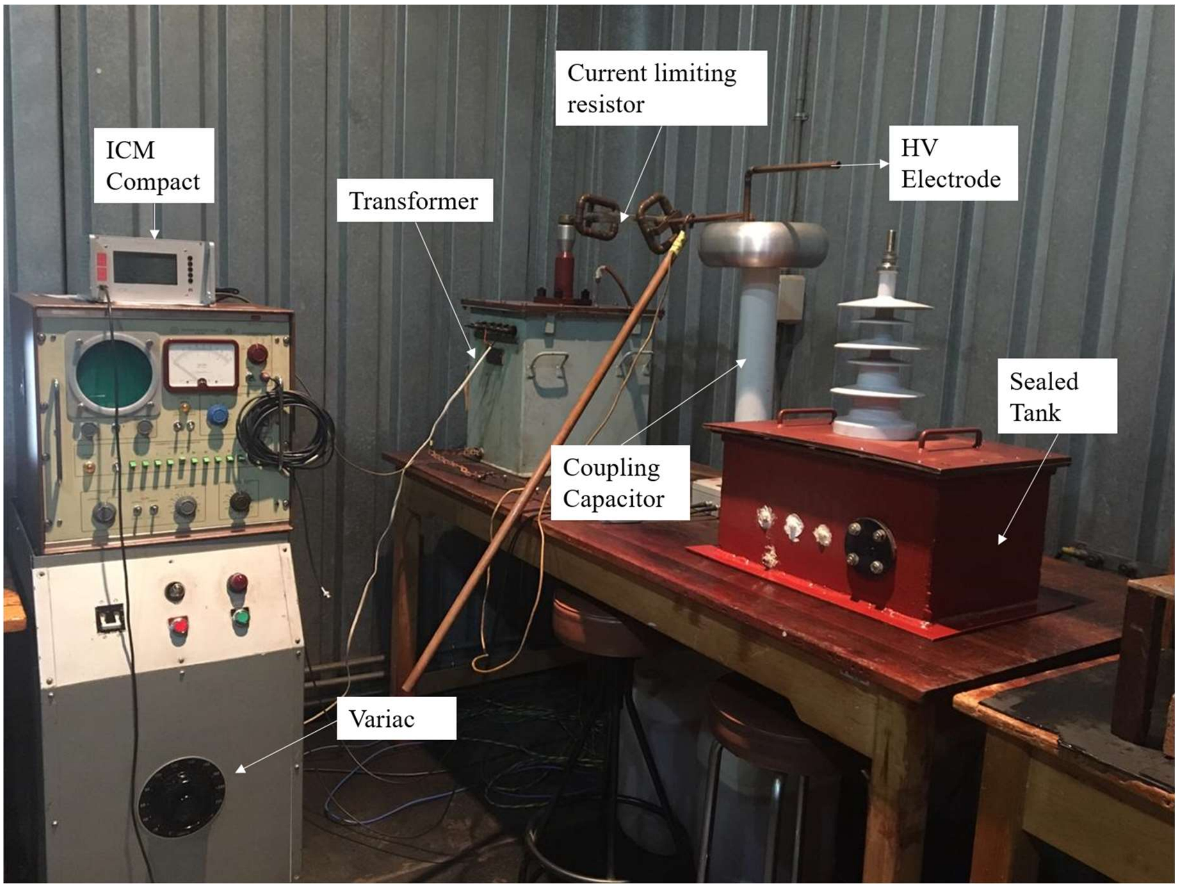


Figure 3-16: Photo of electrical setup for ageing of pressboard sample sets

3.4.3 The Creepage Discharge Ageing Procedure and Measures Taken to Avoid Oil Contamination

The main challenge with handling ester fluids is that they are susceptible to moisture contamination, therefore the handling of oil-impregnated pressboard samples as well as the oil is an important consideration during the execution of the experiments. Figure 3-17 presents the procedure for ageing pressboard samples while avoiding moisture ingress and sample contamination.

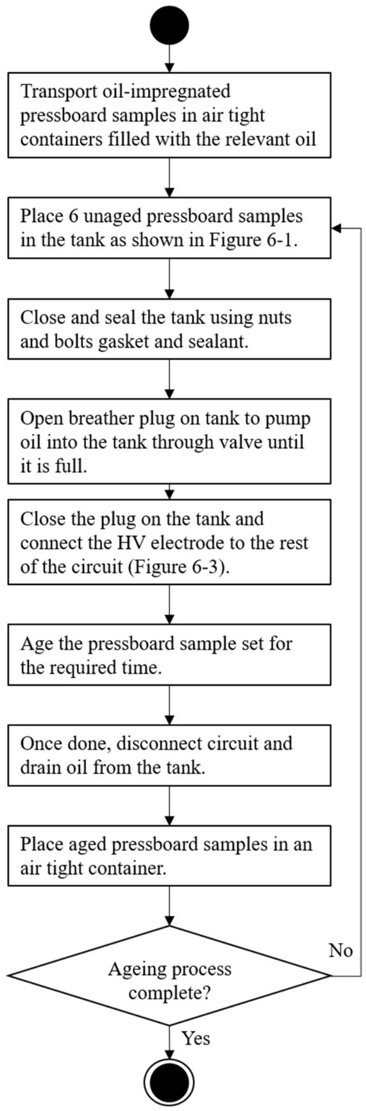


Figure 3-17:Ageing procedure and sample handling

The abovementioned procedure begins with ensuring that the oil-impregnated pressboard samples are not contaminated (or exposed to moisture) as they are transported from the manufacturer to the high voltage lab. This is ensured by placing them in sealed containers that are filled with the respective oil as shown in Figure 3-3.

The samples are then placed in the sealed tank as shown in Figure 3-13 and Figure 3-14. The tank is then closed and sealed to avoid contact with atmospheric air moisture during the experiment. Open the breather plug on the top of the tank to pump oil into the sealed tank using the bottom valve. The tank is then closed up and connected to the rest of the electrical circuit (Figure 3-15) and the electrical ageing (exposure to surface partial discharges) process begins and lasts for 3 hours or 7 hours.

When moving on to testing the next sample set, de-energize and disconnect the electrical circuit, remove the aged pressboard samples and place them in an air tight container so they may be used in the breakdown voltage tests (see 3.5). Empty the tank and store the used oil in a marked container (to be disposed off later). Place the next sample set in the (now empty) tank, seal the tank and fill with the relevant oil and age samples for the required time. Repeat this process for 3-hour aged ester oil-impregnated pressboard, 3-hour aged mineral oil-impregnated pressboard, 7-hour aged ester oil-impregnated pressboard and 7-hour aged mineral oil-impregnated pressboard samples. The surface discharge aged oil-impregnated pressboard test specimens would be ready for the dielectric strength tests together with the unaged specimens as presented in the next chapter.

3.4.4 Conclusion

This chapter presents how multiple pressboard samples are aged (6 at a time) for the required amount of time. The importance of correct sample handling is explained together with the procedure followed to avoid exposure to moisture and contamination during the experiment. The most important aspects include storing the samples in airtight containers through-out the process; from sample procurement, to the ageing experiment phase and finally after the samples have been aged. Although ester fluids are most susceptible to moisture, the same process is also used when handling the mineral oil samples to ensure all test specimens are subjected to the same conditions. The aged samples stored in airtight containers are then subjected to breakdown voltage tests which are detailed in 3.5

3.5 The Breakdown Voltage Tests of the Creepage Discharge-aged Oil-impregnated Pressboard Samples

Following the multiple sample ageing experiments conducted in 3.4, breakdown tests were conducted on the specimens to determine the pressboard's ability to withstand breakdown after being exposed to sustained surface partial discharges.

3.5.1 Test Procedure

The electrically aged pressboard samples from the ageing experiment (explained in 3.4are transferred to the electrode setup shown in Figure 3-18. The electrodes are applied where the surface partial discharges occurred. The electrode setup is immersed in the relevant oil for the respective tests. This is done to remove the possibility of invalid flashovers during the breakdown tests. The tests are done in accordance with the IEC 60243 standards (section 8 and 9) [39].

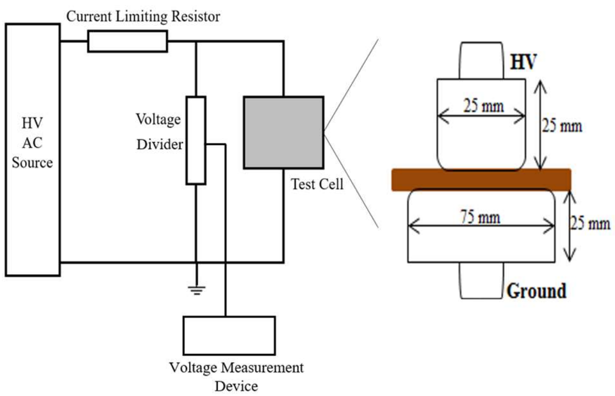


Figure 3-18: Electrical circuit arrangement for AC breakdown tests

The electrodes used in the configuration shown above have a rounded edge with a radius of curvature of 3 mm as specified in the standard. The current limiting resistor that was used is a 1 kΩ distilled water resistor and the breakdown voltage tests were conducted under ambient atmospheric conditions at an altitude of 1800 m above sea level.

The breakdown tests were conducted by applying an AC voltage which was increased step by step (in increments of 5 ±1 kV) until breakdown was reached. At each step (or level) the voltage was kept constant for a period of 1 minute. After breakdown had occurred manifesting as a sudden drop to zero of the measured voltage, the pressboard sample was replaced with the next specimen to be tested, and the oil replaced with new oil. The maximum voltage reached before breakdown is recorded.

The chart shown in Figure 3-19 depicts the breakdown voltage test procedure.

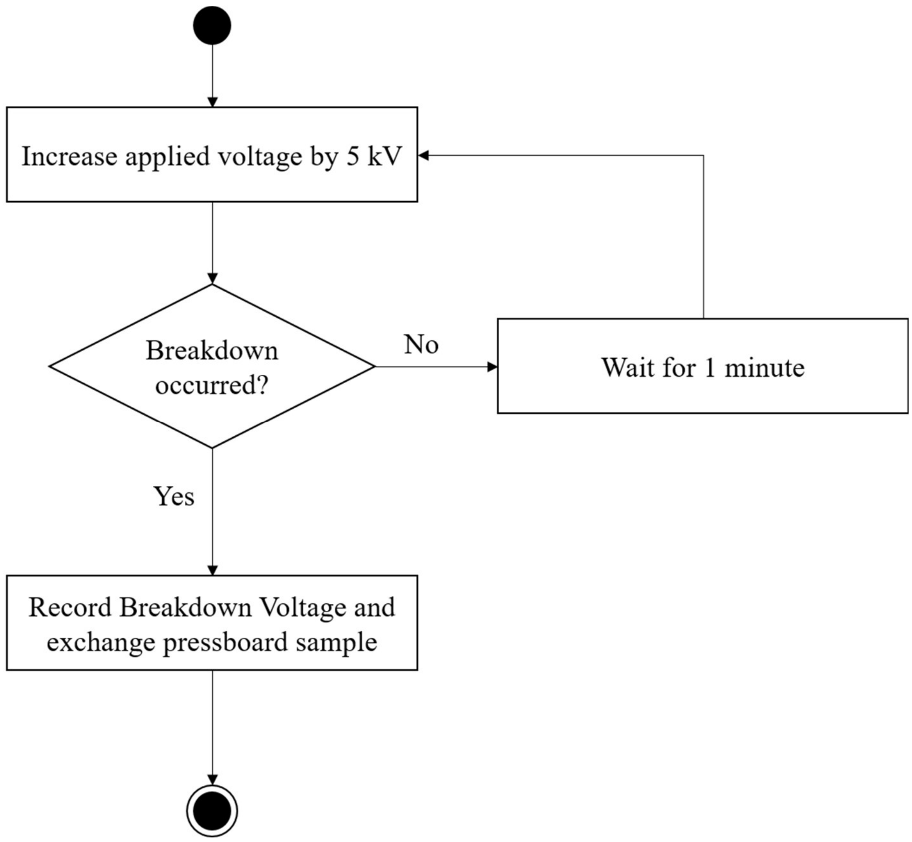


Figure 3-19: Breakdown Voltage Tests Procedure

The test specimens that were subjected to breakdown voltage are the pressboard samples from the ageing experiment and as shown in Table 3-2. Breakdown voltage tests were conducted on the aged ester oil-impregnated pressboard samples to determine their ability to withstand breakdown voltage once they have been exposed to surface partial discharges. Breakdown voltage tests were also conducted on the aged mineral oil pressboard samples for comparison. Unaged samples from both oil types were also tested for control purposes. The obtained results are presented in the next chapter.

3.5.2 Conclusion

The breakdown voltage tests were conducted in accordance with the standards IEC 60243. Aged pressboard samples that had been exposed to surface partial discharges for 0, 3 and 7 hours and kept in an airtight container were subjected to breakdown voltage. The unequal electrode configuration was used, and an AC voltage was applied in steps (with a 1-minute break) until breakdown occurred. The breakdown voltage results and the statistical analysis are presented in the following chapter.

Chapter 4 – Breakdown Voltage Test Results

4.1 Introduction

AC breakdown tests were done according to the procedure shown in 3.5above. The pressboard samples that were tested were subjected to surface discharges for 0, 3 and 7-hour time periods for both mineral oil and natural canola-based natural ester fluid. This chapter presents the breakdown voltage test results of the creepage discharge-aged oil-impregnated pressboard test specimens.

4.2 Breakdown Voltage Test Results

The breakdown voltage test values grouped per oil type and ageing period and the pressboard samples are shown in Table 4-1.

Table 4-1: Breakdown Voltage in kV Test Results

Unaged Pressboard Samples breakdown voltage in kV		
Sample #	**Mineral Oil (kV)**	**Ester fluid (kV)**
1	34.60	38.98
2	35.89	39.23
3	36.20	38.60
4	36.43	38.88
5	36.77	39.36

3-Hour Aged Pressboard Samples breakdown voltage in kV		
Sample #	**Mineral Oil (kV)**	**Ester fluid (kV)**
6	30.80	37.96
7	32.80	38.20
8	33.20	38.60
9	33.40	38.88
10	33.98	39.36
7-Hour Aged Pressboard Samples breakdown voltage in kV		
Sample #	**Mineral Oil (kV)**	**Ester fluid (kV)**
11	28.40	34.80
12	28.97	35.30
13	29.20	35.67
14	30.70	35.74
15	31.10	36.70

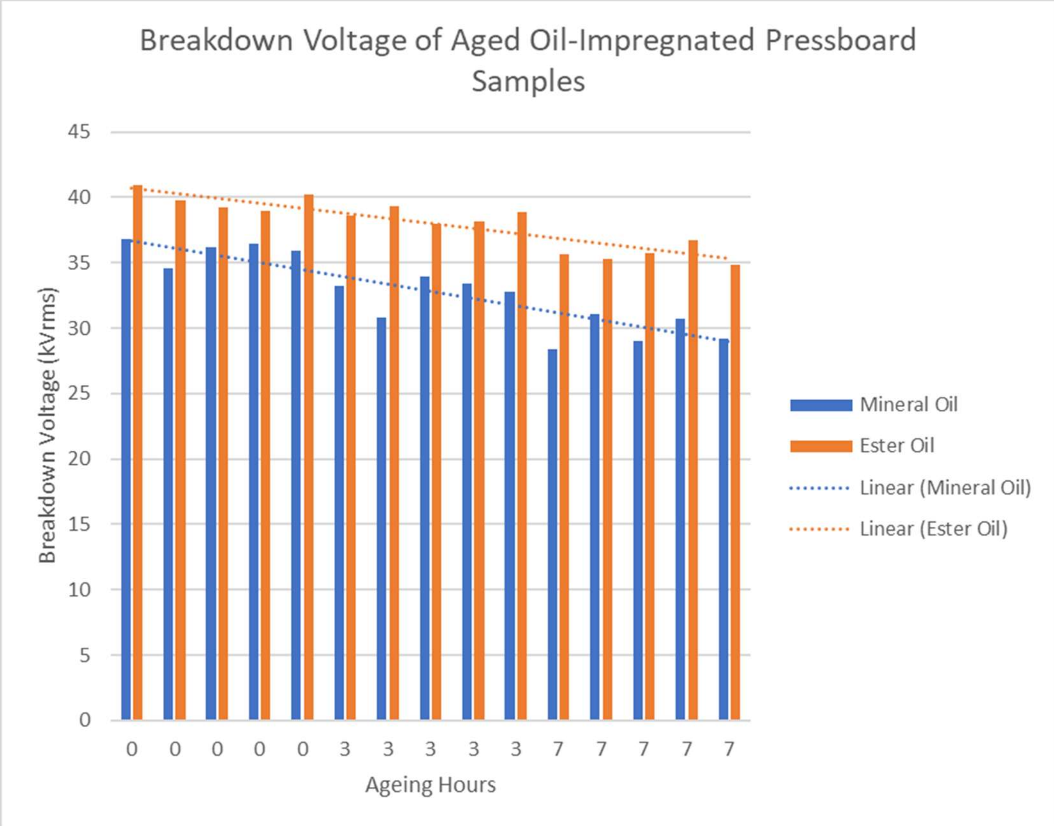


Figure 4-1: Breakdown Voltage of Ester and Mineral Oil-impregnated pressboard exposed to creepage discharges for different periods

As expected, the breakdown voltage of ester oil-impregnated pressboard is generally higher than that of mineral oil-impregnated pressboard throughout all test samples. According to this test set, breakdown voltage of the pressboard in ester fluid is 12% to 20% higher than the breakdown voltage in mineral oil. Moreover, 3 out of 5 of the 7-hour samples in mineral oil had visible burnt marks (which would have developed into punctures) after being subjected to breakdown, whereas the ester oil-impregnated pressboard samples did not have a burn mark after being subjected to breakdown.

In addition, the breakdown voltage decreases as the number of exposure to partial discharges ageing hours increase for both oil types. As the pressboard samples are aged from zero to 7 hours, the breakdown voltage (and insulation capabilities) dropped by approximately 22% for mineral and ester oil-impregnated pressboard. The trendlines of the data from both oil types are parallel (Figure 4-2). This suggests that the breakdown mechanisms are similar in both oils, despite their different properties and chemical structures. Furthermore, Figure 4-2 shows that the deviation in the breakdown voltage is greater in mineral oil than it is in ester fluid.

An in-depth analysis and discussion of the breakdown mechanisms in ester fluid and mineral oil is provided in Chapter 5

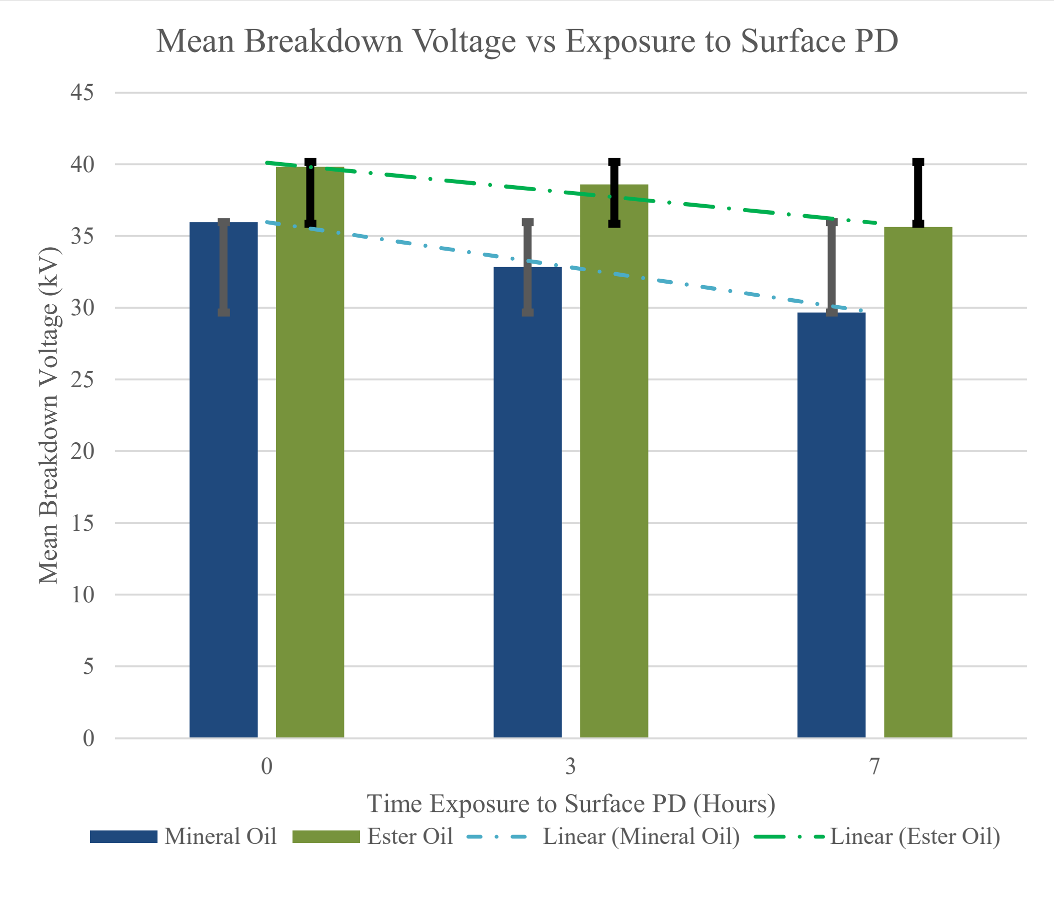


Figure 4-2 : Average Breakdown Voltages of the oil impregnated pressboard vs Time Exposure to Surface PD

4.3 Statistical Analysis of Results

Statistical analysis methods are used to generalise and extrapolate the performance of the experiment with the basis being the observed results in the relatively small data set (5 data points per set) from the breakdown voltage tests [40]. A mathematical model for this behaviour is in the form of a probability density function (PDF). The Weibull distribution functions are chosen for the analysis of such results, as they are the commonly used methods in the analysis of HV electrical insulation tests [40].

4.3.1 Weibull Distribution Analysis Introduction

The Weibull distribution is extensively used in engineering applications due to its high versatility and its simplicity [40]. The PDF of the three-parameter Weibull distribution is shown in equation 1 below.

$$f(x) = \frac{\beta}{\alpha}\left[\frac{x}{\alpha}\right]^{(\beta-1)} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

Where β is the Weibull slope or shape parameter, η is the scale parameter and γ is the location parameter. However, for the analysis of the breakdown voltage results, it is sufficient to assume that γ=0. The model dictates the behaviour of the function including the failure rate (or breakdown probability) over the life span of the transformer.

$$P_F = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{2}$$

The two-parameter Weibull distribution was used to predict the reliability and life data of the mineral oil and ester oil-impregnated pressboards respectively. The probability density function (PDF), cumulative distribution function (CDF) and the probability of failure (P_F) shown in equation 1 and 2 were used to determine the parameters of the Weibull distribution that will make the model fit the data.

4.3.2 Weibull Distribution Results

The Weibull distribution graph in Figure 4-3 illustrates the probability of failure as well as the voltage at which failure occurs (breakdown voltage) for each of the pressboard samples under test. Refer to Appendix A for the Weibull calculations.

The model clearly demonstrates that as the exposure time to surface discharges is increased, the ability of pressboard samples (for both mineral and ester oil-impregnated pressboard) to withstand breakdown decreases. This suggests that the effects of the creepage discharges result in the deterioration of the pressboard, thus reducing the breakdown voltage.

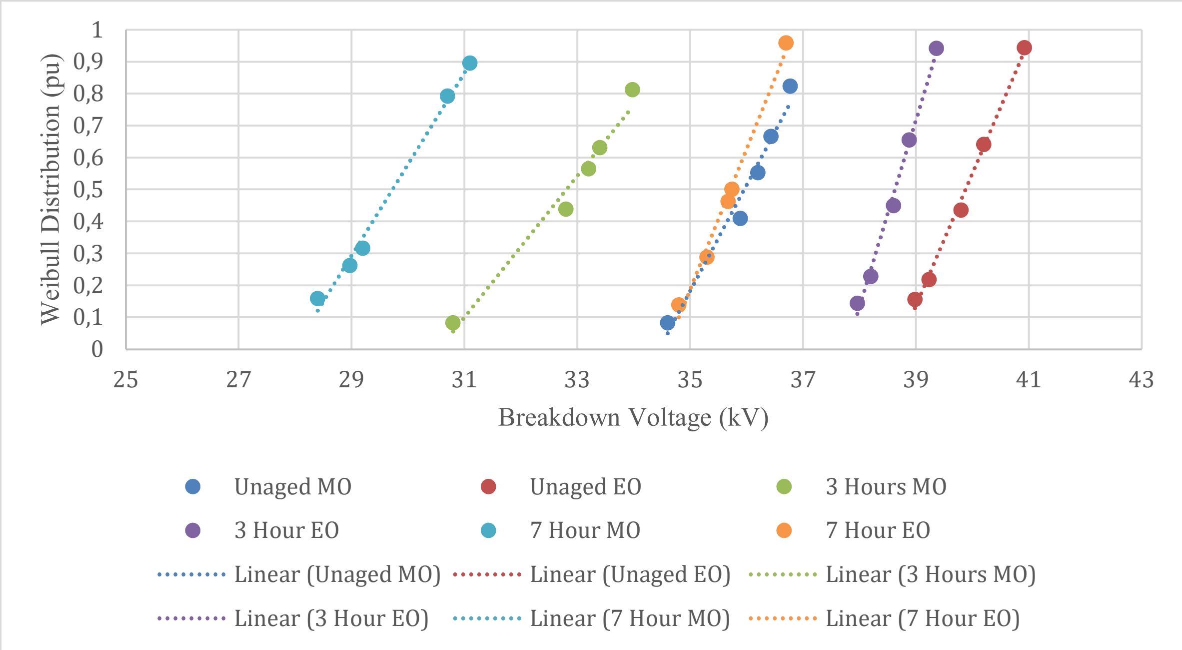


Figure 4-3: Weibull Distribution of Breakdown Voltage Test Results

It is interesting to note that the Weibull distribution for the unaged (brand new) mineral oil-impregnated pressboard overlaps with the Weibull distribution model of the ester oil-impregnated pressboard that has been exposed to surface discharges for 7 hours. This further justifies the fact that the life-time of a transformer maybe be extended by the use of ester oil-impregnated pressboard. It is interesting that the slopes of all the lines in the graph are approximately the same which suggests that the breakdown mechanisms are similar in both cases. An in-depth analysis of how the surface discharge mechanisms in the respective oils resulted in the differences in breakdown voltage is provided in Chapter 5

4.4 Conclusion

The breakdown voltage results show that the breakdown voltage decreases with an increase in the time exposure to surface partial discharges. This is due to the increased insulation deterioration which reduces the insulations ability to withstand breakdown in the case of both the samples impregnated with mineral oil and those with ester fluid. The results show that the breakdown voltage of mineral oil is lower than ester fluid by approximately 20%. The Weibull distribution model of the breakdown voltage results verify this analysis. The probability of breakdown occurring at a higher voltage is higher for cases where the time exposure to surface partial discharges is low, as well as for ester oil-impregnated samples. In addition, it was found that an unaged mineral oil-impregnated pressboard breaks down in a similar way as a 7-hour aged pressboard sample. This strongly suggests that ester fluid perform better than mineral oil in terms of dielectric properties.

Chapter 5 – Discussion and Analysis of the Physiochemical Phenomena on the Relationship between Creepage Discharge and Breakdown Strength

5.1 Introduction

The following sections explain the physics and phenomena that led to the results obtained in the previous sections. This chapter discusses and analyses surface discharge mechanisms and how they affect the resultant breakdown voltage of both the mineral oil-impregnated pressboard and the ester oil-impregnated pressboard samples.

The effects of creepage discharges on the breakdown voltage of ester oil impregnated pressboard were investigated using the experimental setups and procedures presented in the chapters 4 and 6. The investigation was conducted for creepage discharges occurring on pressboard immersed in mineral oil and compared to canola-based natural ester oil-impregnated pressboard. The experimental processes were in two main parts namely, the ageing process where the respective pressboard samples were exposed to varying durations of creepage discharges (chapter 4) and the AC breakdown voltage tests (chapter 6). The main observations, findings and highlights from the investigation are summarized in Table 5-1.

Table 5-1: Summary of Observations and Results

Observations and Results Summary	
Ageing Process	Bubbles formed in the oil as surface PD propagated
	White marks formed on the surface of the pressboard due to the loss of moisture
	Carbon tracking from needle point towards ground plane
Breakdown Voltage Tests	Ester oil-impregnated pressboard samples succumb to breakdown at higher voltages than mineral oil-impregnated pressboard
	The Weibull distribution of the breakdown voltage results show that ester oil-impregnated pressboard has the probability to fail at higher voltages than mineral oil-impregnated pressboard samples

The present chapter discusses the physiochemical mechanisms that govern the creepage discharge process as well as the AC breakdown phenomena of pressboard. Furthermore, the chemical differences in the properties of mineral oil and ester fluid are also used to explain the results observed in this investigation.

5.2 A comparative analysis of breakdown mechanisms in Ester Oil-impregnated Pressboard and Mineral Oil-impregnated Pressboard

The creepage discharge-induced ageing process results in the degradation of cellulose within the pressboard insulation. This breaks up the glucosidic bonds and produces glucose. Glucose can further degrade to form water, carbon dioxide, carbon monoxide, hydrogen and other molecules. In order to reduce the rate of cellulose degradation, moisture ingress needs to be minimized.

It is known that as the transformer insulation ages, there is a significant increase in the moisture content of the insulation system. However, since pressboard has a high affinity for water, the moisture is mostly held in the pressboard instead of the oil. The presence of moisture in pressboard results in increased dielectric losses, which may lead to a decreased dielectric strength and thus a lower breakdown voltage.

In the case of ester fluids, moisture is continuously drawn out of the pressboard due to the hydrophylic nature of ester fluids. Therefore, the rate of insulation deterioration decreases, resulting in pressboard insulation that can last much longer within a transformer and can withstand a higher breakdown voltage. A further analysis is provided in the following sections.

5.3 Mechanisms through which creepage discharges degrade the oil-impregnated Pressboard

With reference to the test cell electrode geometry illustrated in Figure 3-8 in Chapter 4, creepage discharges propagate along the surface of pressboard due to a triple junction geometry that is formed between the pressboard, oil, and needle point. The physiochemical and electrical mechanisms that promote the generation of creepage discharges are discussed in the following sections.

5.3.1 The physiochemical mechanisms associated with creepage discharges on oil-impregnated pressboard

In order to understand the damage or deterioration that occurs on pressboard due to creepage discharges, it is important to first understand the effects that partial discharges have on the chemical composition of the pressboard. One of the mechanisms is cracking reactions.

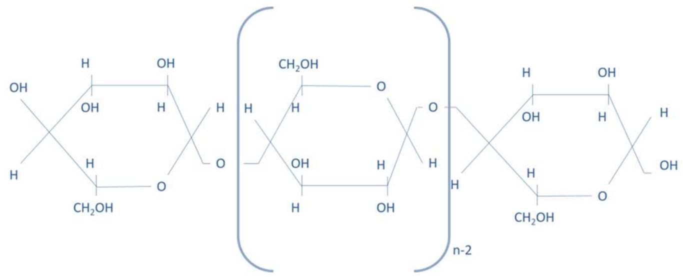


Figure 5-1: Chemical structure of pressboard

Pressboard Deterioration Due to Cracking Reactions

The chemical structure of pressboard is shown in Figure 5-1. When pressboard is exposed to partial discharges, hot electrons impact the cellulose chains. This results in the cracking of the chemical bonds [38]. "Cracking" is a chemical reaction which results in the breaking of the bonds in the cellulose chains. Depending on the incident angle of the charged particles as well as the energy of the bond, the cracking reaction may occur at any position of the chain. The cellulose chain breaks up when the cracking reaction occurs at the glycosidic bond or the pyran ring. However, when the cracking reaction occurs at the groups on the pyran ring, low molecular weight products are formed [38].

In addition, the local temperature on the pressboard surface increases significantly when creepage discharges form. In fact, the temperature of a positive streamer in transformer oil can reach values as high as 5000 K (4 726 °C) according to Flint et al. [41]. These high temperatures cause the vibration of the pressboard chemical groups which subsequently results in pyrolysis of the cellulose. This thermal decomposition further causes changes in the chemical composition of the pressboard. The cracking reactions of the pyran ring at the C1-O and C2-C3 bonds, the glycolaldehyde and the four-carbon molecule are shown in Figure 5-2.

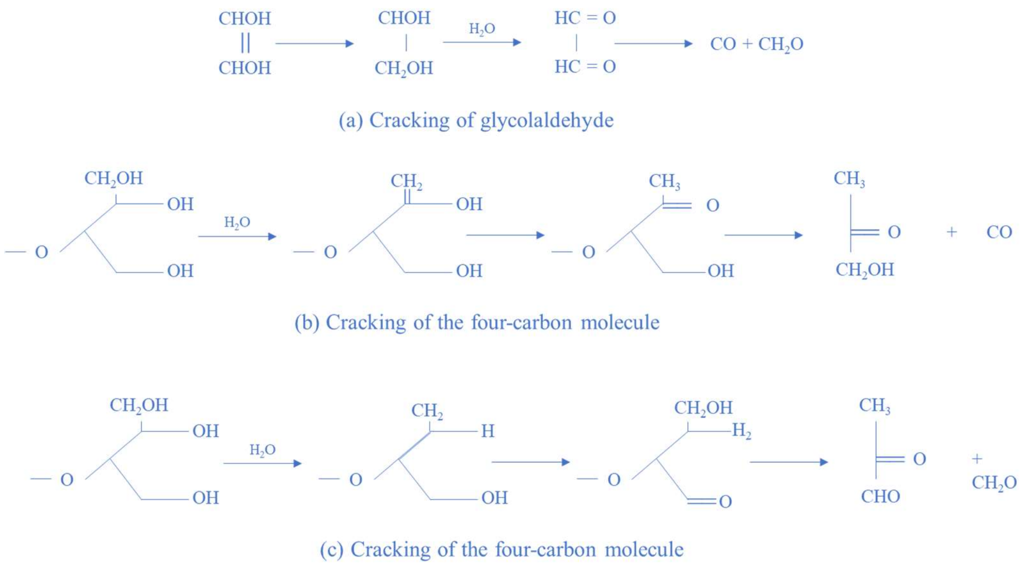


Figure 5-2: Cracking reactions that result in pressboard deterioration [38]

The cracking reactions that occur on the pressboard as a result of exposure to creepage discharges change the topography or morphology of the pressboard. The Fourier transform infrared (FTIR) spectroscopy (done by Y. Li, K. et al. [38]) of pressboard exposed to different partial discharges showed that with increased exposure to partial discharges, the contents of ketone, aldehyde, ester and carboxyl groups on the surface of pressboard increased [38]. As the creepage discharges intensify, the cracking reactions (both due to the hot electrons and the pyrolysis) progressively damage the pressboard. Another mechanism through which creepage discharges damage pressboard is oxidation.

Pressboard deterioration due to oxidation processes

Another way that creepage discharges cause the deterioration of the pressboard is through oxidation processes. Oxidation occurs due to the oxygen (that is dissolved in the transformer oil) reacting with the hydroxyl and alcoholic hydroxyl group in the glucose monomer. This reaction forms carboxyl and ketone groups while decreasing the occurrence of hydroxyl groups. This reaction process is demonstrated in Figure 5-3.

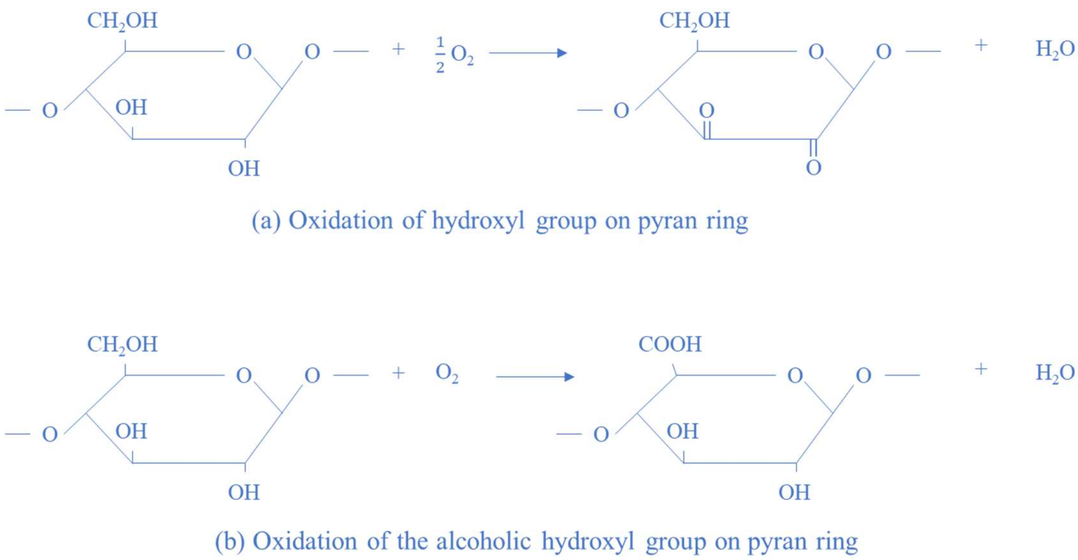


Figure 5-3: Oxidation Process of Cellulose on the Pressboard Surface

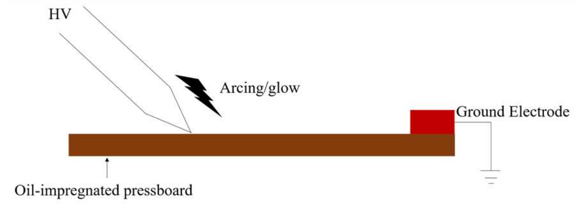
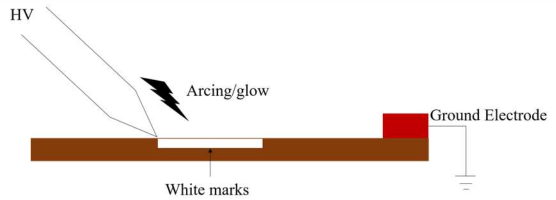
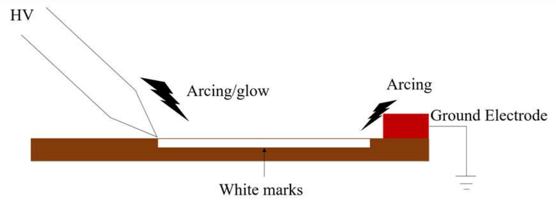
Furthermore, creepage discharges may impart energy in photons prompting the oxygen to convert into ozone which will continue to react with the above oxidized cellulose and lead to an increase in the ester group content. As the transformer insulation ages, there is a significant increase in the moisture content of the insulation system. Oxidation produces moisture which also gradually damages the pressboard insulation as moisture facilitates the formation of acids that further cause chemical degradation. The increased moisture also increases the dielectric losses in the pressboard which in turn increase heat that further accelerates the ageing of the pressboard.

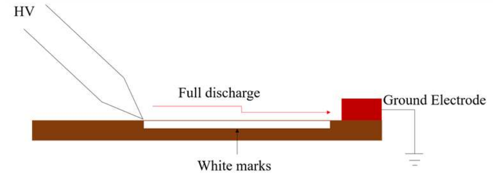
In addition to the physiochemical processes caused by creepage discharges, there are accompanying electrical processes.

5.3.2 Electrical Mechanisms of Creepage discharges on Pressboard

The creepage discharges' behaviour that were observed in the present work were similar to those also reported by Zainuddin et al. [42] as presented in Table 5-2 for the observations made in the present work. Under the influence of a high voltage, the increase in electrical field resulted in the formation of creepage discharges on the surface of the pressboard. White marks formed from the needle point approaching the ground plane while bubbles were observed on the edges of the white marks during the ageing process. In addition, a post-mortem analysis of the pressboard samples indicated that carbon tracking eventually occurred on the surface from the needle point to approximately halfway through to the ground plane (see Figure 5-4). The electrical mechanisms that promote the generation and propagation of creepage discharges are the memory effect of solid surfaces for the hetero space charges as well as the residual low-density channels that are left by previously generated discharges [43]. This is the deposition of space charge on the discharging surface that further influence the subsequent discharge process such as discharges occurring in the zero-crossing of the AC waveform as explained in more detail in the next section.

Table 5-2: Surface discharge progression observations taken from Y. Li, et al. [38]

<table>
<tr><td>a)</td><td>
</td><td>• Early stage
• Arcing discharge or glow at needle tip</td></tr>
<tr><td>b)</td><td>
</td><td>• White marks developed and propagate towards the ground electrode, about halfway across the gap distance</td></tr>
<tr><td>c)</td><td>
</td><td>• White marks almost reach the ground electrode
• Repetitive arcing discharge at the ground electrode to connect the white marks</td></tr>
</table>

d)		• Full discharge event • Can re-occur with or without repetitive earth arcs

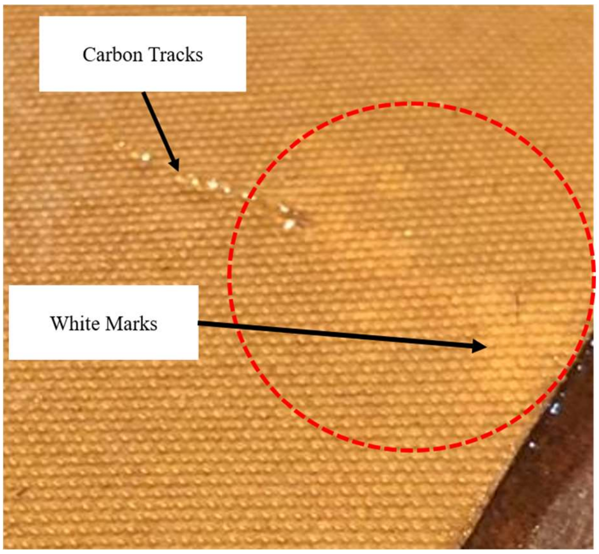


Figure 5-4: Deterioration marks on pressboard surface

Influence of space charge in creepage discharge mechanisms

Surface discharge mechanisms are influenced by the transformer oil properties, solid insulation properties and the waveform polarity and magnitude of the applied voltage. In the acute angle needle-plane electrode configuration, which was used to generate creepage discharges in the present work, the partial discharge polarity is the same as the polarity of the tip of the needle electrode. After the occurrence of a discharge, the area around the needle and the pressboard surface would retain the same polarity charges. Once the voltage polarity is reversed, the local electric field is increased due to the space charge retained from the previous half cycle. This increase in localized electric field promotes the development of the next discharge which in turn results in the propagation of creepage discharges along the surface of the pressboard. Figure 5-5 shows a top view sketch of the space charge effect and how it influences the generation of partial discharges along the surface of pressboard under the influence of a high voltage source.

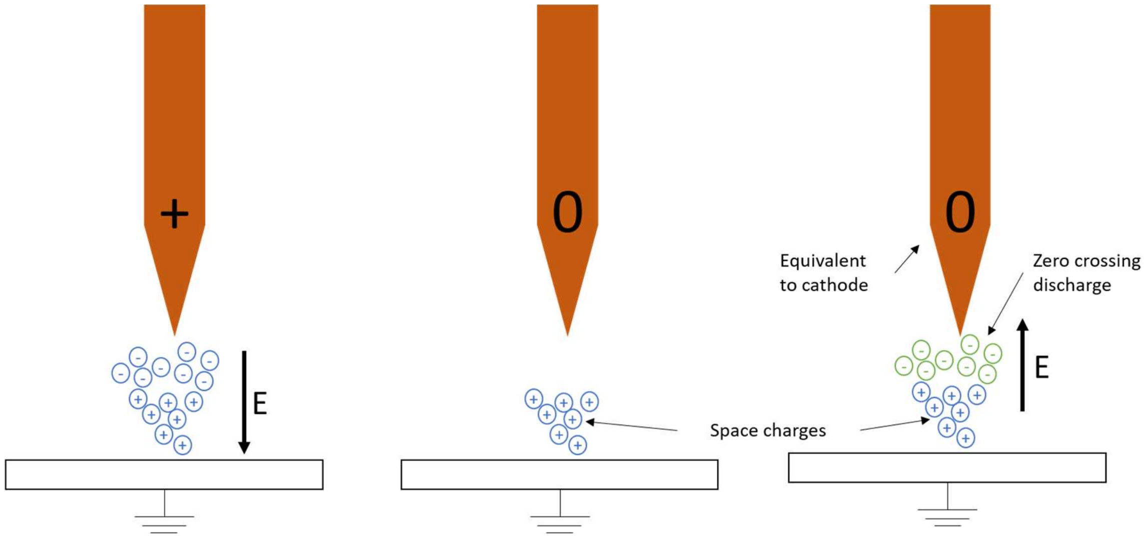


Figure 5-5: The Space Charge Effect

The sketch in Figure 5-5. shows that if the voltage polarity is positive, many of the negative space charges are attracted by the needle point and the positive space charge would remain in the streamer channels [43].

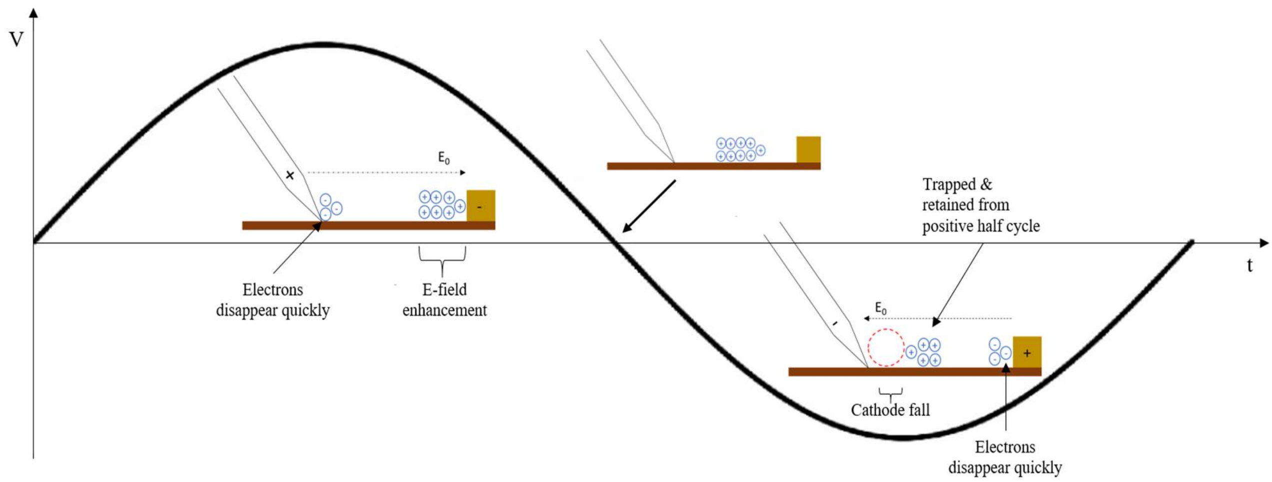


Figure 5-6: The Space Charge Effect in the initial condition [44]

As the polarity reversal approaches; that is at the zero crossing, the voltage is zero and the positive space charges generate an electric field *E* in the direction of the needle point which is at zero potential. The needle electrode behaves as a cathode at this point and a negative polarity discharge is initiated. The higher the voltage, the more charges are dispelled from the needle electrode to the streamer channels, and more space charge is retained by the pressboard surface, thus compounding the generation and propagation of creepage discharges due to the space charge effect. This model shows how the presence of the residual positive space charges promotes the development of the next discharge.

The morphology of the pressboard surface further intensifies the space charge retention process as solid insulation blocks the spatial propagation of streamer channels thus making the space charges reside on the surface for much longer [45]. According to Nakamura et al. and FitzPatrick et al. [46, 47], oil-impregnated pressboard can retain space charges for approximately 50 minutes. Figure 5-6 demonstrates the space charge effect with reference to the AC supply voltage. The surface discharge processes that occur in the positive half-cycle, negative half-cycle as well as at the zero-crossing are summarised below [44].

- The electron avalanches occur in the region of high intensity electric field
- Hot electrons impart energy on the transformer oil and pressboard surface resulting in physiochemical degradation
- Positive charges get trapped under the surface of the pressboard and influence the resultant electric field in the next half-cycle. Therefore, as time progresses more space charges are trapped causing further electric field enhancement, resulting in more intense electron avalanches
- As the pressboard degrades due to the discharges, carbon is deposited into the discharge tracks.

Figure 5-7 demonstrates the space charge effect as ageing occurs.

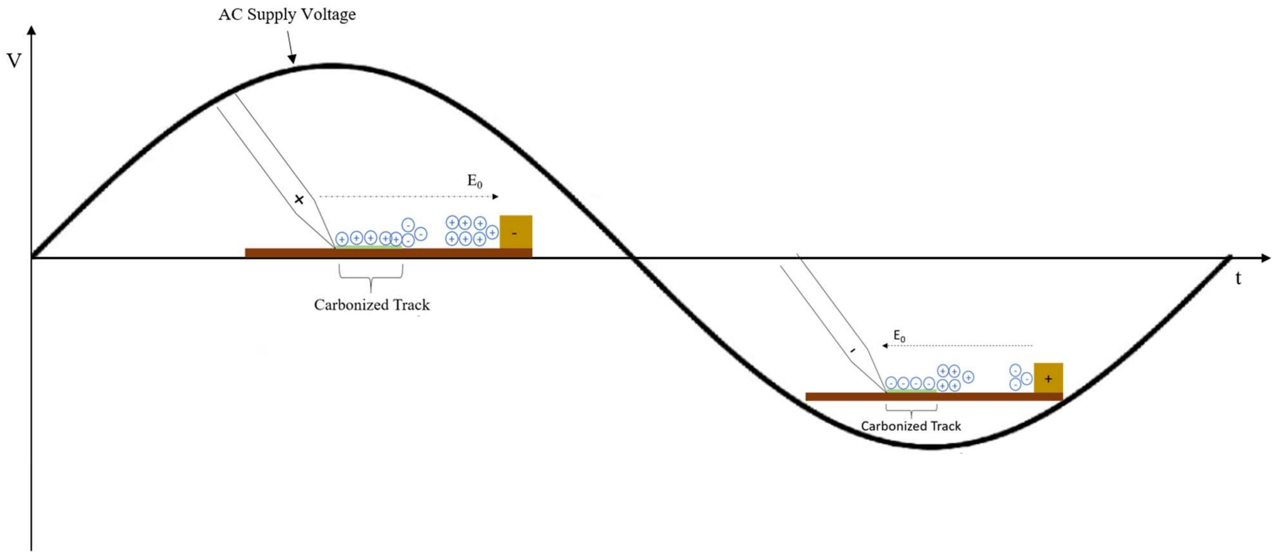


Figure 5-7: The Space Charge Effect in the aged condition [44]

During the aged condition (depicted in Figure 5-7), the carbon tracks formed from the initial processes effectively extend the needle tip which in turn decreases the electrode gap ***d*,** thus increasing the intensity of the electric field [44].

Current flows in the carbonized tracks heating up the oil. This makes the oil less viscous, therefore it becomes easier for electron avalanches to form. Since ester fluids are more viscous than mineral oil, the rate of thinning in the discharge tracks is less.

Creepage discharges Due to Residual Low-Density Channels

The formation of bubbles on the edges of the white marks were observed during the progression of creepage discharges. The streamer channels that form include a gaseous phase of low density due to the vaporization of the transformer oil which is caused by the excessive heat [43]. These low-density channels (with high internal pressure) rapidly consolidate their pressure with that of the surrounding transformer oil. This is observed as the expansion of the streamer channels and the bubbles that form. Furthermore, the bubbles or residual low-density channels are easily retained on the pressboard surface due to the abovementioned memory effect of solid insulation. The low-density oil channels facilitate easier ionisation. The initiation and development of subsequent partial discharges is therefore promoted by the presence of the residual low-density channels.

Pressboard samples for both transformer oil types degraded due to exposure to surface discharges. The causes for the different observations made in ester oil-impregnated pressboard and mineral oil-impregnated pressboard respectively have been found to be due to the cracking reactions, oxidation processes, electrical field stress as well as the space charge effect. Further differences were observed in the AC breakdown of ester oil-impregnated pressboard and mineral oil-impregnated pressboard which are explained in detail in the following section.

5.4 AC Breakdown phenomena of pressboard insulation

The requirements of a good insulating material are that it must have low dielectric losses, high dielectric strength and good mechanical properties. The voltage above which an insulator loses the desired insulating properties and starts behaving like a conductor is the breakdown voltage of the insulator. In the present investigation, the breakdown voltage is used to evaluate the ability of the insulation to withstand breakdown/ flashover after it has been exposed to deterioration and damage during the creepage discharge-induced ageing process. This property demonstrates the quality of the ester oil-impregnated pressboard in comparison with the mineral oil-impregnated pressboard after exposure to creepage discharges for varying durations.

The breakdown mechanisms in solid insulation, such as the impregnated pressboard, depend on the voltage magnitude as a function of time that the voltage is applied modelled as in Equation 1.

$$V_b = \ln (t_b) = k \qquad (1)$$

The variation of breakdown voltage with the time of application is shown in Figure 5-8. The different breakdown mechanisms that occur based on the applied voltage and time of application are shown as different region on the graph [48].

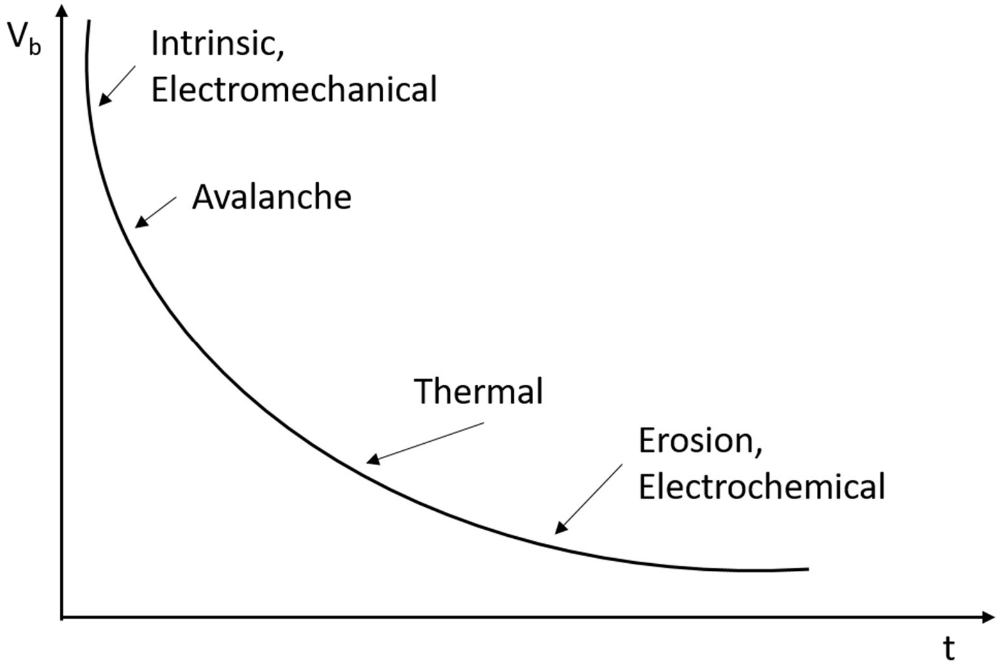


Figure 5-8: Variation of breakdown voltage with time applied [48]

Based on the high voltage applied and the time that it is applied (from the experimental procedure), the breakdown mechanisms of the pressboard insulation are due to electromechanical breakdown. When an electric field is applied to a dielectric material between two electrodes, a mechanical force will be exerted on the dielectric due to the force of attraction between the opposite charges on the electrodes [48]. This compression decreases the dielectric thickness thus increasing the effective stress as is shown in Figure 5-9.

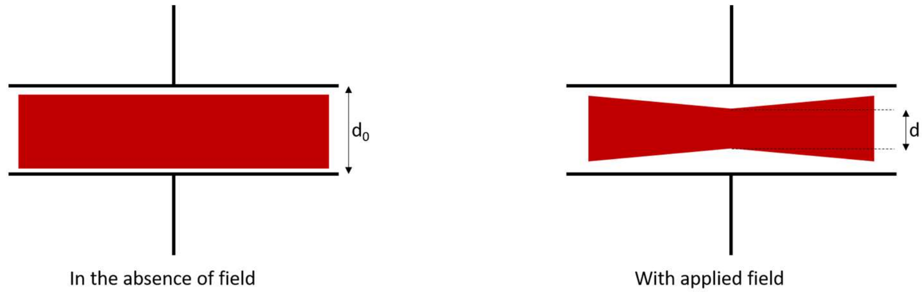


Figure 5-9: Process of electromechanical breakdown

The initial thickness of the insulation slab is d_0 and d is the compressed thickness under the applied voltage. An increased voltage makes the pressboard insulation unstable which results in breakdown. The impact of this breakdown phenomenon is further increased due to the deterioration of the pressboard insulation that has occurred during the creepage discharge induced ageing process.

The strength of the pressboard insulation is that of its weakest region. Since the region between the needle point and ground plane have been subjected to deterioration through the generation of creepage discharges, the pressboard insulation breakdown voltage is determined by the strength of this region. As has been mentioned, the deterioration of pressboard resulted in the presence of moisture and therefore air bubbles are possibly being trapped in the insulation material. For this reason, breakdown across the pressboard is simultaneously facilitated by treeing and tracking occurring as a result of the degradation.

5.5 A comparative analysis of the creepage discharge aged Ester Oil-impregnated Pressboard and Mineral Oil-impregnated Pressboard electrical breakdown results

The observations and results from the experimental section of this investigation have been discussed. Conclusions were drawn to explain the mechanisms and phenomena that resulted in the findings. This is summarized in Table 5-3. The differences in the properties of the mineral oil and natural ester fluid have led to differences in the observations made and breakdown voltage test results. This section discusses these differences.

Table 5-3: Mechanisms leading to the observations and results

Observations and Results Summary		**Mechanism**
Ageing Process	Bubbles formed in the oil as surface PD propagated	Physiochemical and electrical deterioration of pressboard when exposed to creepage discharges
	White marks formed on the surface of the pressboard. In ester fluids the white marks were observed after 30 minutes and at 45 minutes for mineral oil-impregnated pressboard.	
	Carbon tracking from needle point towards ground plane for both cases.	
Breakdown Voltage Tests	Ester oil-impregnated pressboard samples succumb to breakdown at higher voltages than mineral oil-impregnated pressboard	Breakdown mechanisms of pressboard under AC voltage. The pre-established weaknesses in the pressboard due to creepage discharges creates energy in electrical breakdown.
	The Weibull distribution of the breakdown voltage results show that ester oil-impregnated pressboard has the probability to fail at higher voltages than mineral oil-impregnated pressboard samples	

5.6 Conclusion

The investigation into the effects of creepage discharges on the breakdown voltage of natural ester oil-impregnated pressboard versus mineral oil-impregnated pressboard led to various observed discharge characteristics and breakdown test results. These include bubbles, white marks, carbon tracks (on all pressboard samples) and burn marks (on mineral oil-impregnated pressboard only). Furthermore, the breakdown voltage results showed that the breakdown voltage decreased as the time of exposure to surface discharges increased for both oil types. However, the breakdown withstand capabilities of ester fluids are consistently higher than those of mineral oil. This chapter explained in detail the surface discharge mechanisms responsible for the observed discharge characteristics and breakdown test results. These mechanisms include cracking, oxidation, high electric field stress and the space charge effect. The overall results suggest that ester fluids are a viable alternative to mineral oil in power transformers with regard to surface discharges and withstanding breakdown voltage.

Chapter 6 – Conclusion

The investigation into the effects of creepage discharges on the breakdown voltage of natural ester oil-impregnated pressboard versus mineral oil-impregnated pressboard involved two main parts. The pressboard samples were exposed to creepage discharges for 0, 3 and 7 hours for each oil type. The second part involved executing AC breakdown tests. White marks and bubbles were observed during the ageing process. These are due to physiochemical processes such as cracking reactions and oxidation occurring at the pressboard surface. In addition, the electrical mechanisms that resulted in deterioration of pressboard and promoted the development of partial discharges on the pressboard surface are the space charge effect and residual low-density channels. Although the same ageing and breakdown mechanisms occur in both the mineral oil-impregnated pressboard and the ester oil-impregnated pressboard, differences were made in the observations and ester oil-impregnated pressboards were found to be able withstand a higher average breakdown voltage. Ester fluids have a higher dielectric strength than mineral oil, therefore it is expected for ester oil-impregnated pressboard to have a higher breakdown voltage as they have a better ability due to the influence of the ester fluid to withstand breakdown. However, it was observed that ester fluids had more partial discharge activity because of their high viscosity and ability to retain gasses more than mineral oil. The presence of more partial discharges in ester fluids did not translate to more insulation degradation and lower breakdown voltage. This is because ester fluids are hygroscopic and draw moisture out of the pressboard thus slowing down the rate of degradation of the insulation and resulting in higher breakdown voltages than mineral oil.

Table 6-1: Research questions and corresponding answers

Research Question	Answers
What is the effect of surface partial discharges on the dielectric strength of ester oil-impregnated pressboard insulation?	The dielectric strength or breakdown voltage was lowered due to insulation degradation which was as a result of exposure to surface PD
How does the increased time of exposure to surface partial discharges (through the electrical ageing of the samples) on the pressboard insulation further impact the breakdown voltage?	BDV results indicate that as the time of exposure to surface PD is increased, the ability to withstand breakdown decreases. Therefore, the BDV decreases as exposure to surface PD increases and insulation degradation increases.
How do the effects surface partial discharges on the breakdown voltage of ester oil-impregnated pressboard compare and contrast with those on mineral oil-impregnated pressboard?	BDV of MO pressboard samples was 20% lower than ester fluid samples. New mineral oil pressboard sample performs the same as a 7-hour aged EO pressboard sample. This is due to the higher insulation degradation in MO pressboard samples.

In conclusion, this investigation has answered the research questions (mentioned in section 1.3 and Table 6-1) by demonstrating how surface discharges affect the breakdown voltage of both ester oil-impregnated pressboard and mineral oil-impregnated pressboard. The comparison of the results prove that ester fluid can withstand breakdown voltage better than mineral oil-impregnated pressboard when exposed to the same conditions of surface partial discharges. These results, together with the superior ester fluid properties (explained in section 2.2.3), ester fluids provide a viable transformer oil alternative to mineral oil in power transformers. Their use will result in transformers with better fire resistance, that can withstand the effects of surface discharges and are environmentally friendly.

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Appendix A - Weibull Distribution Calculations and Procedure

1. Breakdown voltage data

Sample	MO [kV]	EO [kV]
0	36.77	40.92
0	34.6	39.8
0	36.2	39.23
0	36.43	38.98
0	35.89	40.2
3	33.2	38.6
3	30.8	39.36
3	33.98	37.96
3	33.4	38.2
3	32.8	38.88
7	28.4	35.67
7	31.1	35.3
7	28.97	35.74
7	30.7	36.7
7	29.2	34.8

2. Rank data from lowest to highest

Rank	MO [kV]	EO [kV]
1	28.4	34.8
2	28.97	35.3
3	29.2	35.67
4	30.7	35.74
5	30.8	36.7
6	31.1	37.96
7	32.8	38.2
8	33.2	38.6
9	33.4	38.88
10	33.98	38.98
11	34.6	39.23
12	35.89	39.36
13	36.2	39.8
14	36.43	40.2
15	36.77	40.92

3. Calculate the cumulative probability of failure using the following expression:

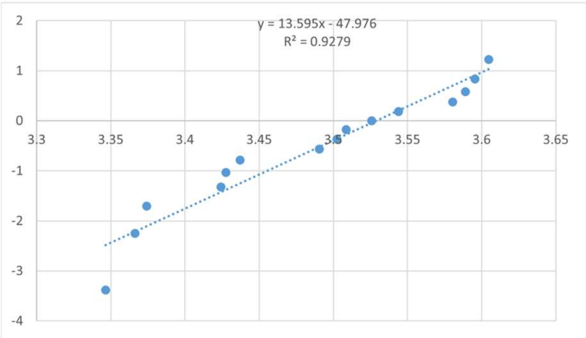
$$P_F = \frac{i - 0.5}{No.of\ samples}$$

Rank	MO	probability	EO	probability
1	28.4	0.0333333	34.8	0.0333333
2	28.97	0.1	35.3	0.1
3	29.2	0.1666667	35.67	0.1666667
4	30.7	0.2333333	35.74	0.2333333
5	30.8	0.3	36.7	0.3
6	31.1	0.3666667	37.96	0.3666667
7	32.8	0.4333333	38.2	0.4333333
8	33.2	0.5	38.6	0.5
9	33.4	0.5666667	38.88	0.5666667
10	33.98	0.6333333	38.98	0.6333333
11	34.6	0.7	39.23	0.7
12	35.89	0.7666667	39.36	0.7666667
13	36.2	0.8333333	39.8	0.8333333
14	36.43	0.9	40.2	0.9
15	36.77	0.9666667	40.92	0.9666667

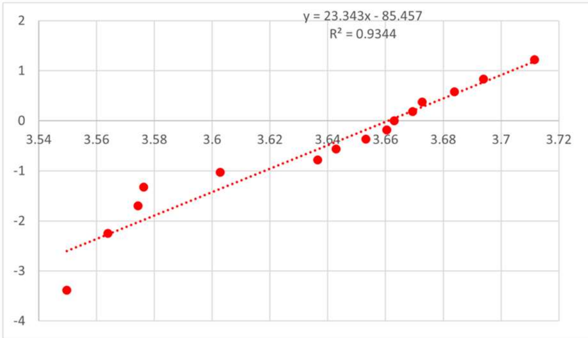
4. Find the value of m and σ_0 in the following expression:

$$\underbrace{ln\left[ln\left[\frac{1}{1-P_F}\right]\right]}_{y} = \underbrace{m}_{slope}\, \underbrace{ln\sigma}_{x} - \underbrace{m\, ln\sigma_0}_{intercept}$$

Rank	MOx	MOy	EOx	EOy
1	3.346389	-3.38429	3.549617	-3.38429
2	3.366261	-2.25037	3.563883	-2.25037
3	3.374169	-1.70198	3.57431	-1.70198
4	3.424263	-1.32538	3.576271	-1.32538
5	3.427515	-1.03093	3.602777	-1.03093
6	3.437208	-0.7836	3.636533	-0.7836
7	3.490429	-0.56566	3.642836	-0.56566
8	3.50255	-0.36651	3.653252	-0.36651
9	3.508556	-0.17883	3.66048	-0.17883
10	3.525772	0.003297	3.663049	0.003297
11	3.543854	0.185627	3.669442	0.185627
12	3.580459	0.375203	3.67275	0.375203
13	3.589059	0.583198	3.683867	0.583198
14	3.595393	0.834032	3.693867	0.834032
15	3.604682	1.224128	3.711619	1.224128



Mineral oil plot



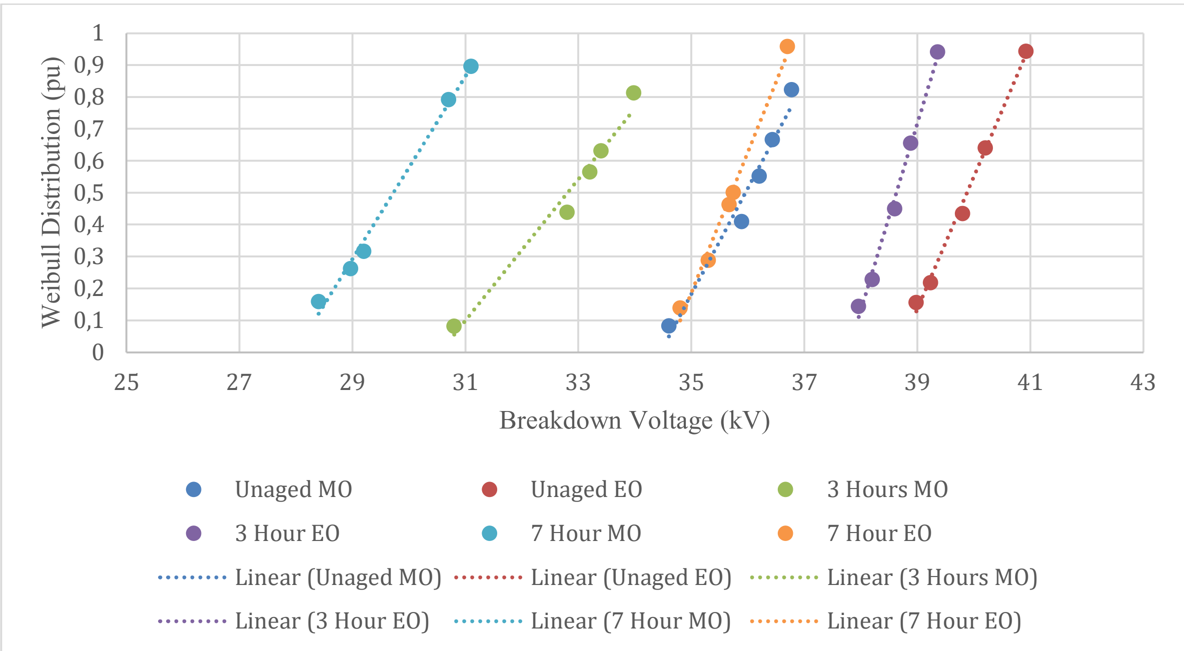
Ester oil plot

Therefore, of m and σ_0 are:

	MO	EO
Shape/Weibull modulus (m)	13.595	23.343
Scale	34.087	38.897

5. Use the Weibull function in MS Excel to calculate and plot the Weibull distribution of the date

WEIBULL.DIST(x, alpha, beta, cumulative)



Appendix B : CIGRE Conference Paper

Effects of Surface Discharges on the Breakdown Voltage of Ester Oil-Impregnated Pressboard Insulation in Power Transformers

B.A NDLOVU, C NYAMUPANGEDENGU

Wits School of Electrical & Information Engineering

South Africa

SUMMARY

Power transformers are currently the most important and expensive equipment in the transmission network. It is therefore imperative that they are properly protected and insulated to ensure resilience. In a transformer, oil is the main insulation material which is also responsible for the cooling of the transformer. Conventionally, the main type of oil that is used in power transformers has been mineral oil. In recent years, however, ester oils (both natural and synthetic) have become the preferred transformer oil option because of their good environmental and safety characteristics. Ester oils are highly biodegradable, have a higher flash and fire point and have better dielectric properties in comparison to mineral oils. Although significant knowledge has been built up on ester oils as insulation, the ester oil insulation technology is not yet mature.

The present work therefore entails investigating the effects of prolonged exposure to surface discharges on the breakdown voltage of ester oil-impregnated pressboard. The results are compared with those of mineral oil-impregnated pressboard. The pressboard samples undergo a preconditioning procedure and are impregnated with canola-based natural ester oil and mineral oil to the same moisture content level. The pressboard samples are then exposed to electrical ageing for 3 and 7 hours and are tested against un-aged samples. Ester oil was found to withstand breakdown voltages up to 20% higher than mineral oil. Generally, a downward trend was observed as the ageing hours increased for both oils. Therefore, the superior dielectric properties of ester oils result in enhanced insulation capabilities over time when compared to mineral oil. The findings of this study enrich the knowledge required to design power transformers that are more resilient to adverse conditions in power systems.

KEYWORDS

Power Transformers, Ester Oil, Breakdown Voltage, Surface Discharges, Pressboard

1. INTRODUCTION

Power transformers are the most important and expensive equipment in the national transmission network, therefore it is imperative that they are designed, operated correctly and maintained regularly to ensure the continued, reliable functioning of the transformer over its life time. The insulation of the transformer forms an integral part in ensuring this continued operation, with an important component being the transformer insulation oil. The function of the transformer oil is to provide cooling whilst improving the insulation properties of the transformer.

The conventional transformer oil type that has been used was mineral oil because it has good dielectric properties and is quite inexpensive to procure. However, as this is the age of environmental consciousness, ester oils are now considered as alternative transformer insulation oil due to their ecological and safety properties. With the introduction of ester oils to the industry, it has become important to understand their properties and how they would interact with the operation of the transformer insulation system in relation to mineral oil. This has led to multiple investigations into the performance of ester oil in comparison to mineral oil. The investigation documented in this report contributes to satisfying this need with the aim of investigating the effects of surface discharges on the AC breakdown voltage of ester oil-impregnated pressboard in comparison to mineral oil-impregnated pressboard.

This investigation is conducted through simulating the ageing of pressboard insulation by electrically ageing the pressboard samples through the generation of surface discharges over time. AC breakdown voltage tests are then performed on these samples to determine how the deterioration in the pressboard insulation affects the insulation level of the insulation in ester oils compared to the insulation in mineral oil.

2. LITERATURE REVIEW

An objective of transformer design is to achieve the best insulation system to withstand high electrical stresses throughout the lifetime of the transformer [1]. The combination of paper and oil (in the form of oil-impregnated paper) is the preferred insulation for its high electrical strength.

Transformer oil is used a cooling medium and provides dielectric strength, hence improving the insulating capabilities. In addition, it protects the solid insulation from contaminants such as moisture and air pockets, and diagnostic tests can be run on the oil to determine the condition of the transformer [2]. Conventionally, mineral oil has been the standard oil used due to its low cost and effective dielectric capabilities; however, the use of (natural and synthetic) ester oils has been introduced as they offer improved safety and environmental properties in addition to their enhanced performance capabilities [3, 4]. Table 0-1 below lists the properties of mineral and both natural and synthetic ester oils [4 – 10].

Table 0-1: Properties of Mineral and Ester Oils

	Units	Mineral Oil	Synthetic Ester Oil	Natural Ester Oil
Biodegradability	%	10	89	97
Flash Point	°C	150	260	316
Fire Point	°C	170	316	360
Fire hazard classification	-	O	K3	K2
Viscosity at 20 °C	mm^2/s	22	70	85
Permittivity at 20 °C	-	2.2	3.2	3.3

From the table above, both ester oils are readily biodegradable, have higher flash and fire points and have better dielectric properties. Furthermore, the use of ester oils results in less paper degradability due to their hygroscopic properties. The only disadvantage of ester oils is that they have a higher viscosity.

Pressboard, utilized in conjunction with transformer oil, is made of multiple compressed layers which have exceptional insulating properties in the form of a high dielectric constant. The disadvantage of using pressboard insulation is that it is sensitive to moisture which may develop due to the normal ageing of the oil-paper insulation system [11,12].

In order to determine the effects on pressboard, it is subjected to electrical ageing through the generation of surface discharges. Surface discharges in power transformers occur due to partial discharges that develop in the interface between the oil and pressboard insulation. The application of a high voltage source increases the localized electric field which leads to the degradation of the solid insulation. Therefore, the surface resistance of the insulator is reduced, thus a high enough voltage source (or high electric field stress), will eventually lead to surface flashover. This is the electrical breakdown which occurs on the surface of the insulator and is a common transformer failure mode [13].

3. EXPERIMENT PROCEDURE

In order to investigate the effects of surface discharges on the AC breakdown voltage of pressboard impregnated with ester oil in comparison to that immersed in mineral oil, the following experiment procedure was implemented.

a. Sample Preconditioning

In order to achieve a controlled experiment, the pressboard samples accordingly undergo the appropriate preconditioning process. This is done to ensure carefully controlled moisture levels and the degree of oil-impregnation. The IEC 60243-1 standard is used to define the process with which pressboard samples are manufactured and impregnated with oil. The pressboard preconditioning process is shown in the flow diagram in Figure 0-1. The main aim of this process is to remove moisture and gasses from the fibrous cellulose pressboard structure and refill the gaps with oil molecules, thus extending the life of the pressboard as an insulator [14]. After the impregnation processes, the oil-pressboard insulation medium effectively forms a composite insulation structure with the oil. The pressboard samples used are pre-compressed and are 90 mm x 90 mm and are 3 mm in thickness.

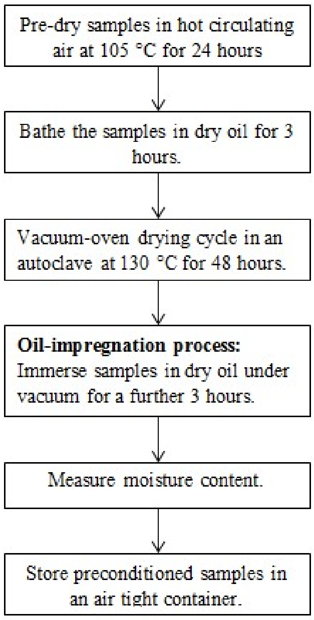


Figure 0-1: Pressboard preconditioning process in accordance with IEC 60243-1.

b. Electrical Ageing or Generating Surface Discharges

The pressboard samples are electrically aged in order to simulate the thermal stress, moisture, acidity and degradation of the pressboard that leads to a decrease in the lifetime of power transformers. The process of electrically ageing pressboard is done by generating surface discharges. In order to investigate the effects of surface discharges on the breakdown voltage, the samples are aged for varying times. For the purpose of this experiment, the samples to be tested will be un-aged, aged for 3 and 7 hours for both ester oil and mineral oil impregnated pressboard samples. The electrical circuit used in generating and measuring the surface discharges formed on the pressboard is shown in Figure 0-2 below.

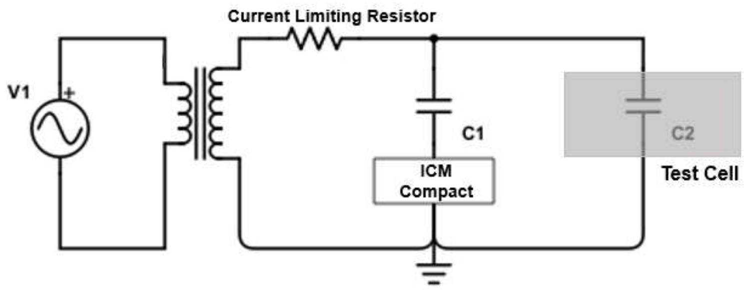


Figure 0-2: Circuit used for surface discharge generation on pressboard

The test object shown above is the needle-plane configuration placed in a sealed tank (to avoid moisture ingress and sample contamination) as shown in Figure 0-3.

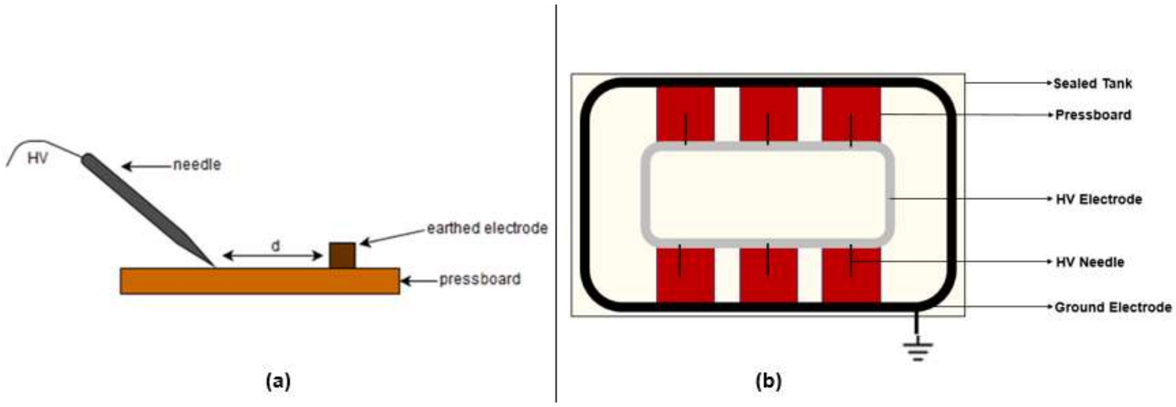


Figure 0-3: (a) Inclined needle-plane electrode configuration (b) Multiple test samples setup

The needle with the high voltage application is placed at an acute angle on the pressboard at a distance *d* from the earthed electrode, which is also placed on the pressboard surface. This method has been found to generate sustainable surface discharges for a sufficient duration to allow for the ageing of pressboard samples with surface discharges [15]. The success in this method is that the acute angle ensures that a strong tangential electric field component is generated, thus minimizing the vertical component which would lead to electrical damage through the pressboard [15, 16].

Electrical ageing was performed in mineral oil and in canola-based natural ester oil, for 3 and 7 hours on 5 pressboard samples per sample set as is shown in Figure 0-3 (b). Therefroe a total number of 30 samples were tested. The applied voltage was 17 kVrms at 50 Hz for a gap distance of 25 mm for a total of 30 pressboard samples.

c. AC Breakdown Voltage Tests

The electric circuit shown in Figure 0-2 is used to investigate and measure the AC breakdown voltage for the unaged and aged pressboard samples. The test cell used for the breakdown tests is shown in Figure 0-4. The applied AC voltage was raised at 1kV/s until breakdown was achieved.

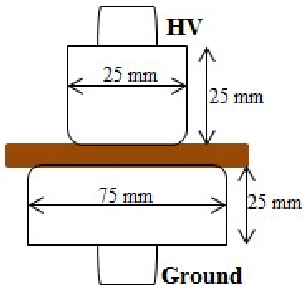


Figure 0-4: Electrode setup for AC Breakdown tests

4. OBSERVATIONS, RESULTS AND ANALYSIS

Figure 0-5 shows the measured partial discharges present in both mineral oil (a) and ester oil (b) for the 3-hour ageing process. It is clear, from the figure below, that the partial discharges in the mineral oil test cell are roughly double the partial discharges occurring in the ester oil test cell at the applied voltage of 17 kVrms. A similar trend is observed in the 7-hour ageing process results.

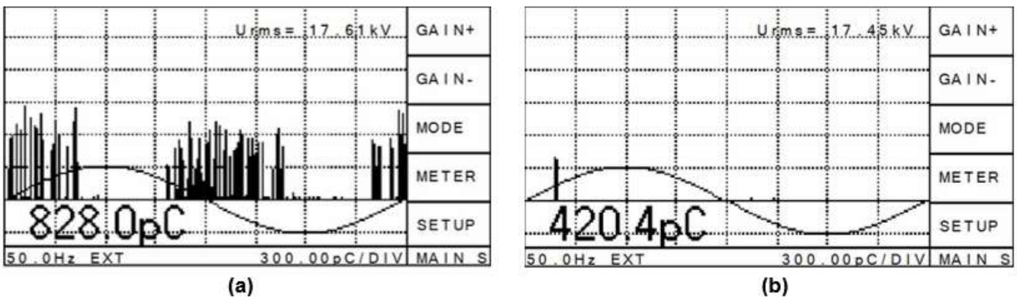


Figure 0-5: Partial Discharges during Ageing Process in (a) mineral oil and (b) ester oil

Since there is a difference in the dielectric properties of mineral and ester oil, it follows that their ability to withstand partial discharge initialization would differ. The partial discharge patterns show that the partial discharges in ester oils, were half of those in mineral oil. Furthermore, it was observed that the 3-hour and 7-hour aged pressboard samples had white carbon-tracks forming on the pressboard from the HV electrode to ground as an indication of surface discharges forming.

The aged and unaged samples underwent AC breakdown as explained in section 3.c. Table 0-2 and Figure 0-6 below show the breakdown voltages for the respective transformer oil samples.

Table 0-2 : Breakdown Voltage per Pressboard Sample in Mineral and Ester Oil

	Breakdown Voltage (kVrms)	
Ageing Hours	Mineral Oil	Ester Oil
0	36.77	40.92
0	34.60	39.80
0	36.20	39.23
0	36.43	38.98
0	35.89	40.20
3	33.20	38.60
3	30.80	39.36
3	33.98	37.96
3	33.40	38.20
3	32.80	38.88
7	28.40	35.67
7	31.10	35.30
7	28.97	35.74
7	30.70	36.70
7	29.20	34.80

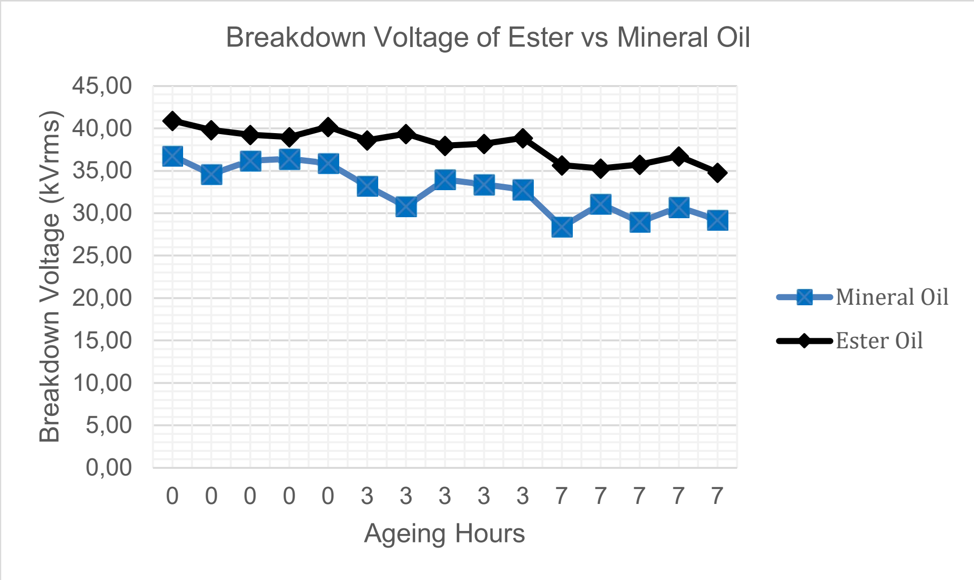


Figure 0-6:Breakdown Voltage in Mineral and Ester Oil

As expected, the breakdown voltage in ester oil is generally higher than that of mineral oil throughout all test samples. According to this test set, breakdown voltage in ester oil is 12% to 20% higher than the breakdown voltage in mineral oil. Moreover, 3 out of 5 of the 7-hour samples in mineral oil had visible burnt marks when subjected to breakdown.

In addition, the breakdown voltage decreases as the number of ageing hours increase for both oil types. As the pressboard samples are aged from zero to 7 hours, the breakdown voltage (and insulation capabilities) dropped by approximately 22% for mineral and ester oil. Furthermore, Figure 0-7 shows that the deviation in the breakdown voltage is greater in mineral oil than it is in ester oil.

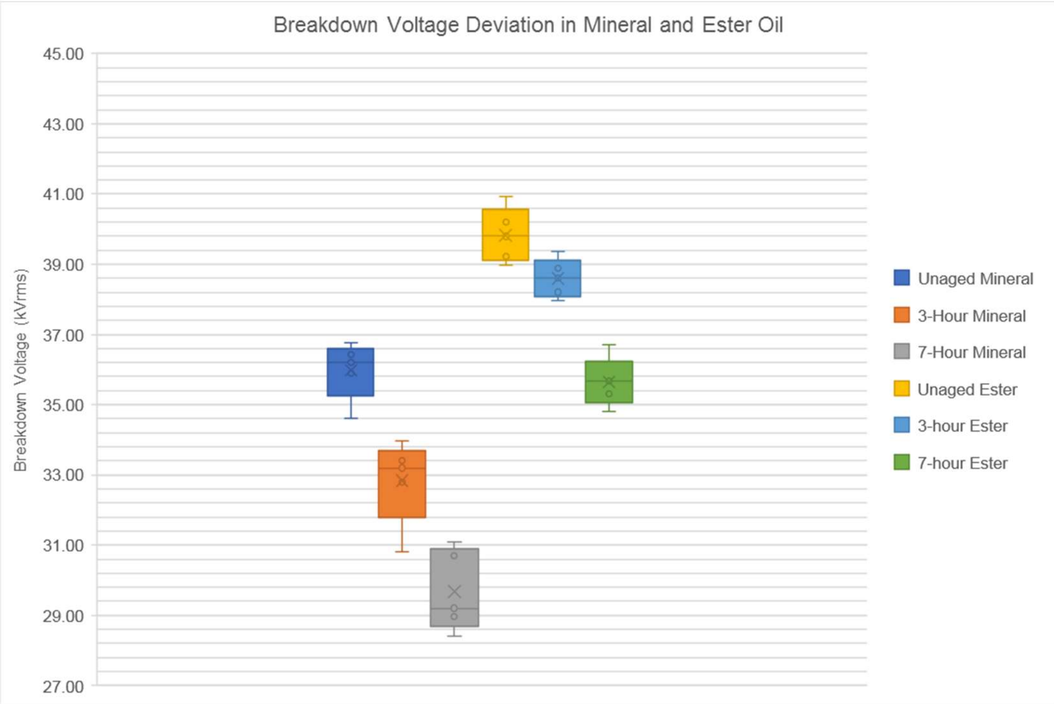


Figure 0-7: Breakdown voltage deviation in mineral an ester oil

5. CONCLUSION

The effects of surface discharges on the breakdown voltage in mineral oil and ester oil impregnated pressboard have been investigated. It was found that when ageing the pressboard samples at 17 kVrms, for 3 and 7 hours, the partial discharges in mineral oil are double those found in ester oil. Once the samples are subjected to an AC breakdown, the results show that ester oil has the ability to withstand breakdown 20% better than mineral oil. However, a general downward trend was observed as the ageing hours increased from 0 to 7 hours. Therefore, the superior dielectric properties of ester oils result in enhanced insulation capabilities over time when compared to mineral oil.

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Appendix C : SAUPEC Conference Paper

Investigating the Effects of Creepage Discharges on the Breakdown Voltage of Natural Ester Oil Impregnated Pressboard in Power Transformers

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Abstract—**Power transformers are the most expensive and important equipment in the transmission network. It is therefore crucial that they are well protected to avoid damage of equipment and possibly loss of life. The common transformer failure modes are due to dielectric failures. The aim of this project is to subject pressboard to creepage partial discharges and investigate the effects on the AC breakdown voltage. Furthermore, since ester oils are considered to have superior characteristics to mineral oil, the effects of creepage discharges on the respective breakdown voltages are investigated and reported. This is done by using an inclined needle-plane electrode configuration, with an electrode gap of 25 mm. Creepage discharges are generated for various times and the pressboard samples undergo breakdown voltage tests. Ester oil was found to withstand breakdown voltages up to 20% higher than mineral oil. Generally, a downward trend was observed as the exposure to creepage discharges increased for both oils. The Weibull distribution model reveals that a brand new mineral oil-impregnated pressboard sample can withstand breakdown at the same level as an ester oil-impregnated pressboard sample that has been exposed to creepage discharges for 7 hours. Ester oils can therefore improve the lifetime of pressboard (and thus the transformer itself) regardless of exposure to insulation deterioration through creepage discharges.**

Keywords—Creepage Discharges, Ester Oil, Breakdown Voltage

INTRODUCTION

The Eskom transmission network has approximately 37000 kilometers of transmission lines. The most important and expensive equipment in this vast network is the transformer. It is therefore imperative that they are protected to ensure the continuity of supply. The main transformer failures are due to dielectric failure modes across all voltage levels. This includes failure that is due to partial discharges, surface tracking and surface flashovers [1 - 3]. Current mineral oil-filled transformer failures are catastrophic and may result in the loss of equipment, continuity of supply and possibly life. Ester oils are proposed as alternative transformer fluids due to their high fire safety and superior environmental properties [4]. Although ester oil properties seem to surpass those of mineral oil, studies are yet to be done to determine whether ester oils can be incorporated into the transformer design. The aim of this work is to contribute to this knowledge by investigating the effects of creepage discharges on the breakdown voltage of canola-based natural ester oil impregnated pressboard. A comparison is done with the effects of creepage discharges on the breakdown voltage of mineral oil impregnated pressboard. This is done by subjecting pressboard samples to surface discharges for various periods and testing the ability of the pressboard to withstand breakdown voltage thereafter. The literature review, experiment methodology and observed results are included in the sections that follow.

BACKGROUND

The purpose of transformer oil in a power transformer is to be used as a cooling medium and as an insulator which provides dielectric strength. Furthermore, diagnostic tests can be run on the oil to determine the condition of the transformer while it in service.

Conventionally, mineral oil has been the standard oil used, however, the use of ester oils has been introduced in the last 40 years as an alternative since they have improved safety and environmental properties and a higher permittivity when compared to mineral oil. Table 1 below lists the properties of mineral and both natural and synthetic ester oils [5 – 10].

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TABLE I. TRANSFORMER OIL PROPERTIES

	Units	Mineral Oil	Synthetic Ester Oil	Natural Ester Oil
Biodegradability	%	10	89	97
Flash Point	°C	150	260	316
Fire Point	°C	170	316	360
Fire hazard classification	-	O	K3	K2
Viscosity at 20 °C	mm2/s	22	70	85
Permittivity at 20 °C	-	2.2	3.2	3.3

Since insulation deterioration as a result of dielectric failure modes is one of the main transformer failure modes, it is important to determine the effects of creepage discharges on pressboard. Surface discharges in power transformers occur due to partial discharges that develop in the interface between the oil and pressboard insulation. The application of a high voltage source increases the localized electric field which leads to the degradation of the solid insulation. Therefore, the surface resistance of the insulator is reduced, thus a high enough voltage source (or high electric field stress), will eventually lead to surface flashover. This is the electrical breakdown which occurs on the surface of the insulator and is a common transformer failure mode.

Several studies have been done to understand the mechanisms that cause creepage discharges which eventually lead to surface flashover. Zainuddin et al. performed extensive studies into the characteristics of partial discharges that are due to surface tracking in oil-impregnated pressboard under AC voltage [11, 12]. Making use of the needle-plane electrode setup, creepage discharges were generated over the pressboard surface until eakdown was achieved. The observations were analyzed in correlation with phase resolved patterns in order to understand surface discharge mechanism.

Due to the differences in the mineral and ester oil properties, it is expected that the surface discharges mechanisms may occur slightly differently, which ultimately results in different breakdown mechanisms.

EXPERIMENT METHODOLOGY

The experiment procedure has two main phases, namely: the ageing process and the breakdown testing phase. The pressboard samples are subjected to creepage discharges for a period of time and then undergo breakdown voltage tests in the respective experiment phases.

The pressboard samples are 90 x 90 x 3 mm and are impregnated with canola-based natural ester oil for the ester oil tests and mineral oil for the mineral oil tests. The impregnation is done by means of a preconditioning process which is in accordance with IEC 60243-1 and is shown in Figure 0-8 below.

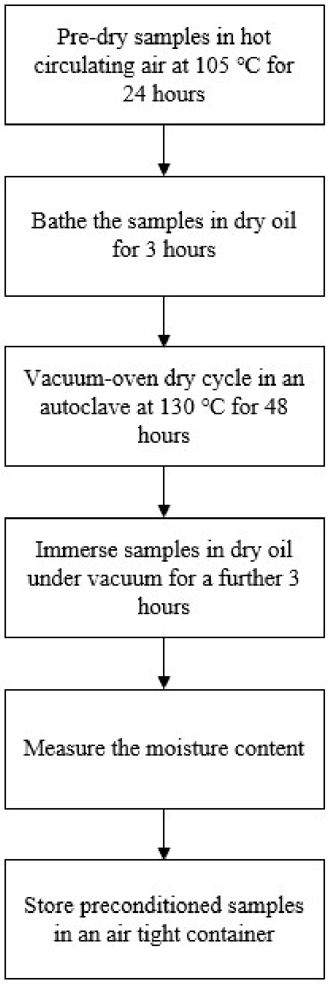

Figure 0-8: Pressboard Preconditioning Process

Phase I:

The surface/creepage discharges are generated (and measured) using AC voltage as is shown in the electric circuit in figure below. The applied voltage is sustained 30 kVrms at 50 Hz.

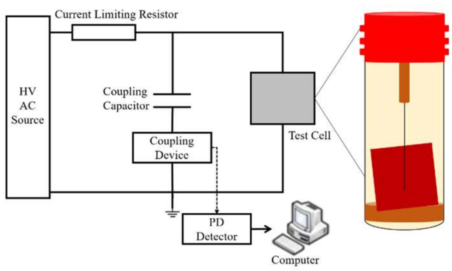

Figure 0-9: Circuit for Surface Discharge Generation

The test object is an inclined needle-plane electrode setup which allows for creepage discharges to be generated on the surface of the pressboard (moving towards the ground plane) without piercing or damaging the pressboard. The electrode gap used in this setup is 25 mm. The entire test setup is placed in a sealed transparent tank (Figure 0-9) which is filled with the transformer oil under test to avoid arbitrary flashover from occurring during the ageing process.

Phase II:

Breakdown tests are performed using the AC circuit from phase I, however the test cell in this case is as shown in Figure 0-10. The electrode setup is immersed in the relevant oil for the respective tests. The breakdown tests are done in accordance with IEC. Voltage is gradually increased until breakdown/flashover occurs. Then the next pressboard sample is tested.

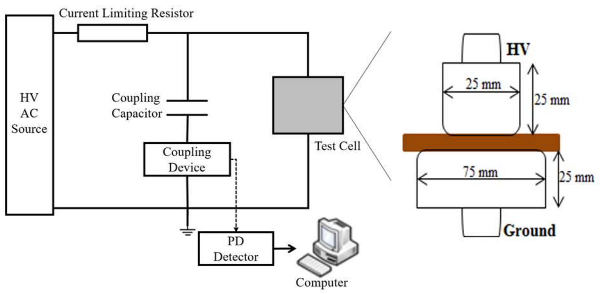

Figure 0-10: Electrical Circuit for AC Breakdown Voltage Tests

OBSERVATIONS, RESULTS AND ANALYSIS/DISCUSSION

The observations, results and analysis of both phases of the experiment are explained in the following sections.

Phase I: Generating Surface Discharges

Creepage discharges are generated on the surface of pressboard samples using the process outlined in experiment methodology above. The creepage discharges that forms during this process were as described in literature [11, 12]. The essential step to the generation of surface discharges is the formation of white marks from the needle point towards the ground plane. The white marks were observed after 30 minutes of the beginning of the ageing process. Figure 0-11 shows the formation of white marks from the needle point.

The re-occurrence of surface discharges develop along the path of the white marks forming carbon tracks but do not extend the full length (25 mm) as shown in Figure 0-11. The carbon tracks are an indication of further degradation of the pressboard insulation.

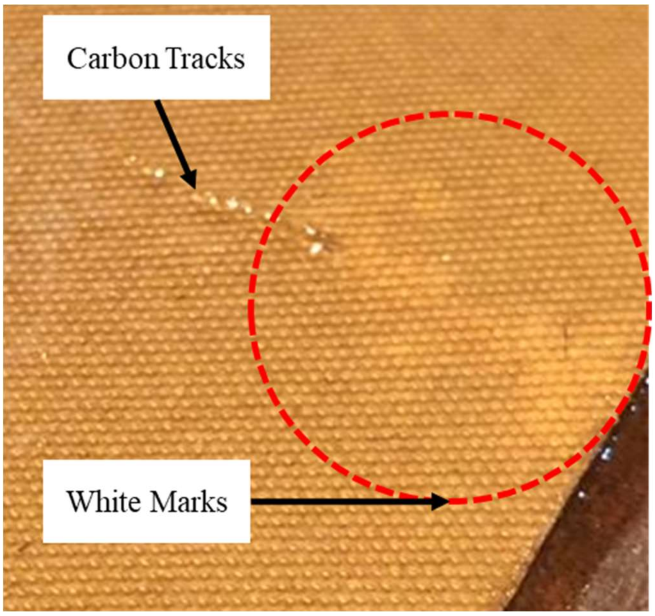

Figure 0-11: Observations of Surface Discharges on Pressboard Sample

The correlation between the observed creepage discharges and the partial discharge phase-resolved patterns (PDPRP) explains the creepage discharge mechanisms for both mineral and ester oil impregnated pressboard.

The first PDPRP plot (Figure 0-13) indicates that although the magnitude of partial discharge activity in mineral oil is much higher than ester oil, the general shape is similar and occurs in the negative half cycle of the AC voltage. This suggests similar surface tracking mechanisms despite the differences in the oil properties.

The second PDPRP plot in Figure 0-13 shows the partial discharge patterns that occur at inception for mineral and ester oil respectively. The partial discharge activity occurring in the third quarter of the AC voltage cycle indicates the presence of corona activity, particularly at the needle point [11, 12].

After a 30 minute period where the propagation of white marks begins to for, the partial discharge pattern changes (from predominately occurring in the negative AC voltage cycle) as shown in the third PDPRP plot. Partial discharge activities are widely spread across both the negative and positive half cycles. There is a significantly high intensity of partial discharge activity occurring covering the entire AC cycle [11, 12].

The mineral oil samples exhibited a decreasing trend in the partial discharge data from the second to the third plot. The decline may be due the reduction electrical field stress due to destructive superposition [11]. During the phase of the formation of white marks, space charges increase, thus increasing the conductivity of the surface which temporarily changes the field distribution in the area.

Phase II: Breakdown Voltage Tests

AC breakdown tests were done according to the procedure shown above. The pressboard samples that were tested were subjected to surface discharges for 0, 3 and 7 hour time periods for the respective oils. The breakdown voltage test results for each pressboard sample are shown in table 2 below.

TABLE II. BDV OF MINERAL AND ESTER OIL IMPREGNATED PRESSBOARD SAMPLES

Mineral Oil Impregnated Pressboard			
Sample Number	**Unaged**	**3 hours**	**7 hours**
1	34.6	30.8	28.4
2	35.89	32.8	28.97
3	36.2	33.2	29.2
4	36.43	33.4	30.7
5	36.77	33.98	31.1
Ester Oil Impregnated Pressboard			
Sample Number	**Unaged**	**3 hours**	**7 hours**
1	38.98	37.96	34.8
2	39.23	38.2	35.3
3	39.8	38.6	35.67
4	40.2	38.88	35.74
5	40.92	39.36	36.7

As expected, the breakdown voltage in ester oil is generally higher than that of mineral oil throughout all test samples. According to this test set, breakdown voltage in ester oil is 12% to 20% higher than the breakdown voltage in mineral oil [14]. Moreover, 3 out of 5 of the 7-hour samples in mineral oil had visible burnt marks when subjected to breakdown.

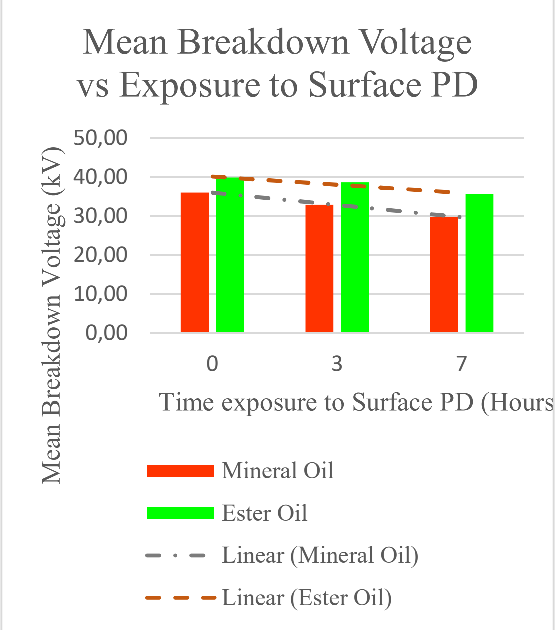

Figure 0-12: Average Breakdown Voltage vs Exposure to Creepage PD

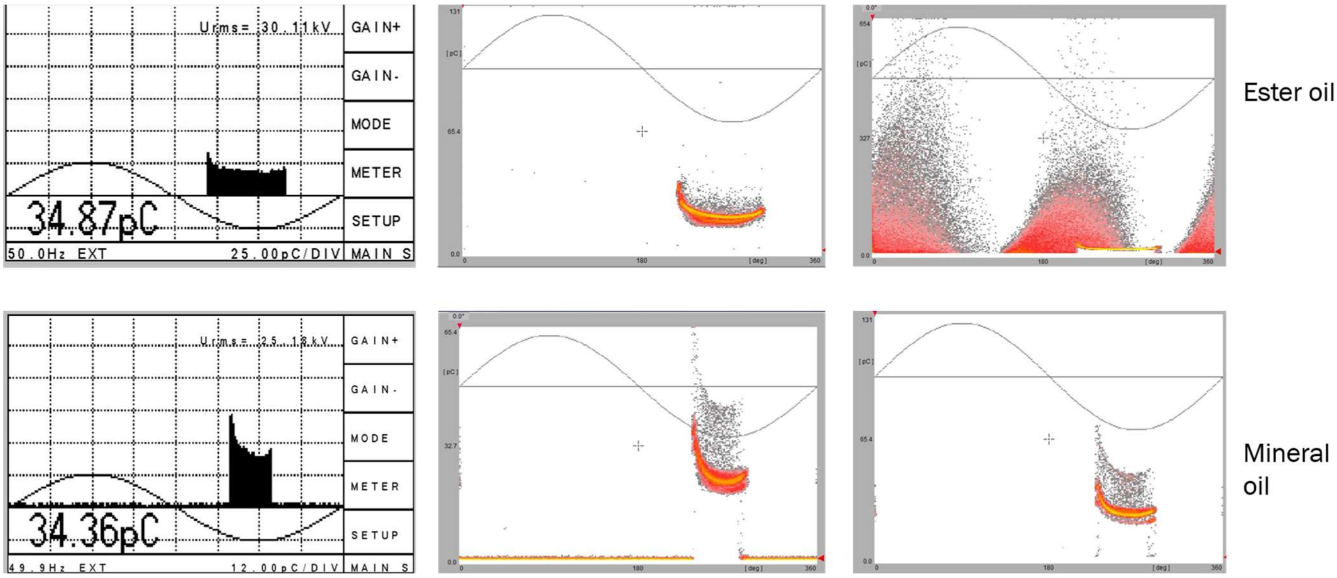

Figure 0-13: PDPRP Plots of Mineral and Ester Oil-Impreganted Pressboard

In addition, the breakdown voltage decreases as the number of ageing hours increase for both oil types. As the pressboard samples are aged from zero to 7 hours, the breakdown voltage (and insulation capabilities) dropped by approximately 22% for mineral and ester oil. The trendlines of the data from both oil types are parallel (Figure 0-12). This suggests that the breakdown mechanisms is are similar in both oils, despite their different properties and chemical make-up.

Furthermore, Figure 0-14 shows that the deviation in the breakdown voltage is greater in mineral oil than it is in ester oil.

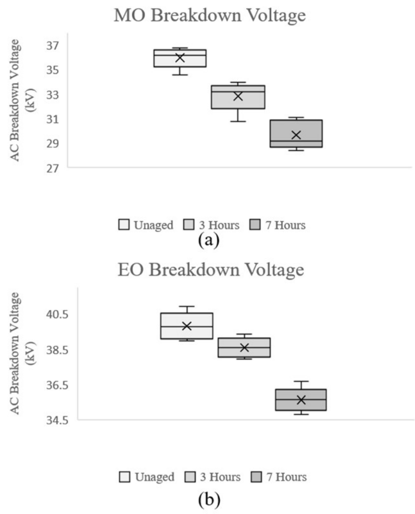

Figure 0-14: Box and Whisker plot of (a) Mineral and (b) Ester Oil Impregnated Pressboard

The Weibull distribution is commonly used in industry to model the time to failure or lifetime of the pressboard samples. Since the lifetie of a power transforer is highly dependent on the solid insulation, the Weibull distribution is a useful tool to predict the lifetime of the transforer as well.

The two-parameter Weibull distribution was used to predict the reliability and life data of the mineral oil and ester oil-impregnated pressboards respectively. The probability density function (PDF) and cumulative distribution function (CDF) shown in equation 1 and 2 below were used to determine the parameters of the Weibull distribution that will make the model fit the data.

$$f(x) = \frac{\beta}{\alpha}\left[\frac{x}{\alpha}\right]^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

$$P_F = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{2}$$

For equation 1 and 2, α,β represent the shape and scale factors of the Weibull distribution respectively. The weibull distribution graph in Figure 0-15 illustrates the probability of failure as well as the voltage at which failure occurs (breakdown voltage) for each of the pressboard saples under test. The model clearly demonstrates that as the exposure time to surface discharges is increased, the ability of pressboard samples (for both mineral and ester oil-impregnated pressboard) to withstand breakdown decreases. This suggests that the effects of the creepage discharges result in the deterioration of the pressboard, thus reducing the breakdown voltage.

It is interesting to note that the weibull distribution for the unaged (brand new) mineral oil-ipregnated pressboard overlaps with the weibull distribution model of the ester oil-impregnated pressboard that has been exposed to surface discharges for 7 hours. This further justifies the fact that the life time of a transformer maybe be extended by the use of ester oil-impregnated pressboard.

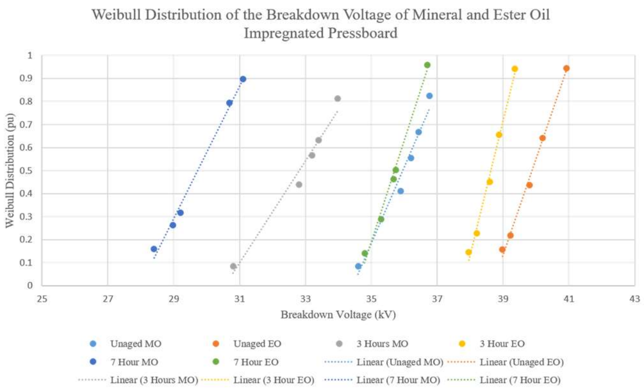

Figure 0-15: Weibull Distribution of BDV

CONCLUSION

Creepage discharges were generated to investigate the effects of this insulation deterioration on the breakdown voltage of ester oil-impregnated pressboard compared to mineral oil-impregnated pressboard. The observed progression of the creepage discharges along the surface of the pressboard included white marks progressing from the needle to the ground plane, as well as carbon tracking. The fact that the PDPRP plots are similar for both oil types, and the average breakdown voltage graph showed parallel trendlines indicates that the creepage discharge mechanisms as well as the breakdown mechanisms are the same in both oil types, regardless of the differences in their properties.

AC breakdown tests reveal that although the breakdown voltage decreases as the time exposure to surface discharges increases, ester oils have proven to withstand a high breakdown voltage than mineral oil-impregnated pressboard. The overlap between the unaged mineral oil and the 7 hour ester oil Weibull distributions further proves that ester oils can be used to improve the life time of the pressboard insulation as well as the transformer as a whole.

Acknowledgment

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