Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis

By

Tahira Arshad

(Registration No: 00000363790)

Department of Electrical Engineering (Power)

US-Pakistan Centre for Advance Studies in Energy (USPCAS-E)

National University of Science and Technology (NUST)

H-12, Islamabad 44000, Pakistan

(2024)

Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis

By

Tahira Arshad

(Registration No: 00000363790)

A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in
Electrical Engineering (Power)

Supervisor: Dr. Muhammad Farasat Abbas

US-Pakistan Centre for Advance Studies in Energy (USPCAS-E)

National University of Science and Technology (NUST)

H-12, Islamabad 44000, Pakistan

(2024)

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS Thesis written by Mr / Ms Tahira Arshad (Registration No. 00000363790), of USPCASE (School/College/Institute) has been vetted by undersigned, found complete in all respects as per NUST Statutes/ Regulations/ Masters Policy, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of Master's degree. It is further certified that necessary amendments as point out by GEC members and foreign/ local evaluators of the scholar have also been incorporated in the said thesis.

Signature: ____________

Name of Supervisor: Dr. Muhammad Farasat Abbas

Date: 30. 5. 2024

Signature (HOD): ____________

Date: 03/06/24

Signature (Dean/ Principal) ____________

Date: 05/06/2024

FORM TH-4

National University of Sciences & Technology

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by Tahira Arshad (363790)

Titled: Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis be accepted in partial fulfillment of the requirements for the award of **MS Electrical Power Engineering** degree with (A) grade.

Examination Committee Members

1. Name: Dr. Syed Abbas Kazmi Signature: ______

2. Name: Dr. Muhammad Yousaf Signature: ______

3. Name: Engr Numan Ahmed Signature: ______

Supervisor's name: Dr. Muhammad Farasat Abbas Signature: ______

Date: 30.05.2024

Dr. Hassan Abdullah
Head of Department

Signature

23-04-24
Date

COUNTERSIGNED

Date: 05/06/2024

A/Dean/Principal
US-Pakistan Center for Advanced Studies in Energy (USPCASE)

CERTIFICATE OF APPROVAL

This is to certify that the research work presented in this thesis, entitled "Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis" was conducted by Ms. Tahira Arshad under the supervision of Dr. Muhammad Farasat Abbas

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the USPCASE NUST in partial fulfillment of the requirements for the degree of Master of Science in Field of Electrical Engineering

Department of USPCASE National University of Sciences and Technology, Islamabad.

Student Name: Tahira Arshad Signature: ____________

Examination Committee:

a) Dr Syed Ali Abbas Kazmi Signature: ____________

....

b) Dr. Muhammad Yousif Signature: ____________

....

c) Engr Nouman Ahmed Signature: ____________

....

Supervisor Name: Dr Muhammad Farasat Abbas Signature: ____________

Name of HOD: Dr Hassan Abduallah Signature: ____________

A/Principal & Dean: Dr. Adeel Waqas Signature: ____________

v

AUTHOR'S DECLARATION

I ......Tahira Arshad...... hereby state that my MS thesis titled "Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis" is my own work and has not been submitted previously by me for taking any degree from National University of Sciences and Technology, Islamabad or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

Name of Student: Tahira Arshad

Date: 30-5-24

PLAGIARISM UNDERTAKING

I solemnly declare that research work presented in the thesis titled "Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes Analysis" is solely my research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero-tolerance policy of the HEC and National University of Sciences and Technology (NUST), Islamabad towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the University reserves the rights to withdraw/revoke my MS degree and that HEC and NUST, Islamabad has the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized thesis.

Student Signature: ____________

Name: Tahira Arshad

DEDICATION

I dedicate this thesis to my beloved father **Muhammad Arshad** and my beloved mother **Zubaida Farzand** for their immense support and prayers, my brothers **Rashid Ali** and **Sajid Ali**, who have been unwavering pillars of support throughout my academic journey. Your love, encouragement, and sacrifices have been the driving force behind my accomplishments. Your unwavering belief in me has been my greatest source of strength. This work is a testament to the values you instilled in me – perseverance and dedication. I am deeply grateful for your love and guidance, and I dedicate this thesis to you with all my heart.

ACKNOWLEDGEMENT

“Read! In the Name of your Lord, Who has created (all that exists). Who created man from a lot of blood. Read! And your Lord is the most Generous, Who taught by the pen. Who taught man that which he knew not” - (Surah Al-Alaq | 96:1-96:5)

All praise to Allah Almighty who gave me the strength and knowledge to do the work presented in this thesis. This research work would never been completed without His will and blessings. I would like to acknowledge the supervision and guidance received from Dr. Muhammad Farasat Abbas throughout this research work. His friendly supervision and motivation brought the best out of me. Working on this project alongside him, I have grown professionally and have polished my research skills.

I would also like to thank the members of my GEC committee Dr. Syed Ali Abbas Kazmi, Dr. Muhammad Yousif and Engr. Numan Ahmed who honored my committee’s presence. I would also acknowledge the Lab Engineer Numan Ahmed of High Voltage Laboratory at USPCAS-E for providing me the space to carry out experimental work involved in this work.

Tahira Arshad

Reg No: 363790

Electrical Engineering (Power) 2K21

USPCAS-E NUST

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

PRPD	Phase-Resolved Partial Discharge
BDV	Breakdown Voltage
PD	Partial Discharge
FTIR	Fourier Transform Infrared
HV	High voltage
AC	Alternative Current
LIV	Lighting Impulse Voltage
PDIV	Partial Discharge Inception Voltage
LI-BDV	Lighting Impulse-Breakdown Voltage

ABSTRACT

Transformer is a cornerstone of electrical power systems, and the most problems occur in it is related to the defects and weakness of the insulation systems. This study aims to contribute to the understanding of the electric field in influencing the breakdown mechanisms of insulating oil in transformers. It investigates the impact of field non-uniformity on breakdown voltage, partial discharge in mineral oil (MO) under AC voltage by considering three different electrode configurations: 1) plane-plane (P-P), 2) needle-needle (N-N), and 3) plane-needle(P-N). In addition, Fourier Transform Infrared (FTIR) spectroscopy is employed to analyze the chemical changes in tested MO samples after exposure to the applied AC voltage under above mentioned three configurations. Also, Weibull statistical analysis is conducted to confirm breakdown voltage conformity across AC setup at a 1.5mm gap in which plane-plane and needle-needle (tip radius= 0.5μm) configurations are identified as quasi-uniform fields with higher AC breakdown voltage (AC-BDV) compared to the plane-needle geometry. Therefore, plane-needle configuration created the highly non-uniform electric field, thereby diminishing the dielectric strength of the tested oil. The impact of electrode configuration on field uniformity is further highlighted by partially resolved partial discharge (PRPD) patterns. Partial discharge analysis primarily examines variations in charge intensity along the edges of plane electrodes and the sharpness of needle tips. Surprisingly, the analysis reveals that the plane-plane configuration setup exhibits the highest partial discharge charge intensity compared to other configurations. The FTIR analysis of the tested oil confirms changes in chemical composition and the degradation of MO samples following exposure to the applied AC voltage under 1,2 and 3 electrode configurations. The chemical degradation of the mineral oil tested through FTIR notices the higher chemical deterioration and furan formation in the plane-plane configuration while almost similar trend is noticed for needle-plane and needle-needle configurations.

Keywords: impurities; partial discharge (PD); breakdown voltage; Weibull distribution; electrode configurations

CHAPTER 1: INTRODUCTION

1.1 Introduction

In a society and technology landscape that continually evolves, maintaining high stability and reliability in power systems is imperative as they underpin our basic standard of living and the everyday operations of industries. The introduction of transformers into the AC network of high voltage dates back to the late nineteenth century [1]. Today, ensuring a dependable power supply heavily relies on the proper functioning of network components devoid of faults, with transformers playing a pivotal role. Despite advancements, most power transformers worldwide still utilize oil-immersed insulation due to their extended lifespan expectancy. Within oil-filled insulated power transformers, three key dielectric materials are commonly employed: paper (lining the walls and windings), oil, and paint. These "three particular lines of defense" are instrumental in preventing arcs, sparks, or partial discharges within the power transformer [2]. A robust insulating system significantly enhances the efficiency and reliability of a power system and its components.

In commonsense terms, the no problem at all activity of high-voltage power transformers pivots significantly on the plan of the protection framework. This is principally because of the different sorts of overvoltage stresses that transformers are presented to during administration. One such stressor is lightning strikes on above lines straightforwardly associated with the power transformer, known as the standard lightning drive (1.2/50μs) [3]. Guaranteeing legitimate protection of the organization is critical for the protected and dependable transmission of electrical power. An extraordinary cover has high protection from mechanical and electrical burdens, alongside life span [4, 5].

Analysis of post-failure incidents of transformers highlights insulation failures as the primary cause of operational breakdowns. For over a century, paper and oil have remained the primary choices for insulating power transformers. Transformer oil permeates the voids within paper insulation, bolstering its dielectric strength by filling gaps among components within the transformer tank. It fills a double need as a protecting liquid and a cooling specialist, scattering heat produced by transformer center and winding misfortunes.

Nowadays, still mineral insulating oil is the most dominated liquid for power transformer networks, due to its widespread and rapid usage over many decades [6, 7]. Mineral insulating oil has several appealing thermal-physical and electrical properties for transformers insulated system. Mineral oil, inferable from its wide accessibility and moderateness, has been a staple decision for oil-filled protected transformers across different voltage evaluations starting from the origin of the transformer business. It is the favored protecting fluid for power transformers because of its expense viability, productive warm cooling capacities, low pouring point at low temperatures, high proficiency, and prepared accessibility in the transformer market [8].

Under routine operating conditions, the insulation system of power transformers experiences thermal and electrical stresses. These stresses and reactions can lead to faults and cause the insulation system to deteriorate within just a few years of operation. Consequently, monitoring the transformer's condition, particularly its insulation system, is vital to ensure the equipment's extended lifespan.

1.2 Transformer Insulating Oil Deterioration and Breakdown

Breakdown strength is one of the most important and fundamental parameters of insulating liquids. Insulation is crucial in electrical systems because it protects and prevents current leakage, reduces energy losses, and ensures that equipment operates safely and reliably throughout its service life. The breakdown of liquid insulation is marked by a sudden surge in current, which is highly undesirable and unsafe [9]. While transformer oil can maintain its insulating properties after such breakdowns, its quality does deteriorate to some extent. Breakdown in transformer insulating mineral oil can occurs under different voltage conditions, including both AC (Alternating Current) and lighting impulse voltage [10]. These breakdown mechanisms are necessary to comprehend and to ensure the safe and reliable working of transformers. When voltage exceeds the oil's dielectric strength while subjected to AC voltage, insulating mineral oil can experience breakdown and failure before time. Similarly, partial discharges (PD) can also occur within the oil when subjected to high voltage, producing localized sparks or discharges in oil. These PD events can weaken and deteriorate the insulation over time, eventually leading to the fully breakdown phenomenon if left unaddressed [11-14]. AC voltage causes thermal stress in the oil during operation, eventually causing it to heat up [15]. Excessive temperature can decrease the oil's dielectric strength and desire properties and contribute to breakdown. Impulse voltage, characterized by high-energy short-duration pulses, introduces its own set of breakdown mechanisms, and creates high electrical stress at specific points within the transformer. This concentration of stress could result in breakdown if it exceeded the insulating oil's dielectric strength. Impulse voltage may initiate streamers of electrical discharges that propagate within the insulating oil. If these streamers discharges develop into full-path propagations and keep growing, they can lead to complete breakdown [16].

Understanding these breakdown mechanisms in both AC and impulse voltage conditions is essential for transformer maintenance and safety. Regular routine testing, such as monitoring for partial discharges and measuring the dielectric strength, helps to detect potential issues before time, allowing for timely maintenance or replacement to prevent catastrophic failures and secure the continued reliable operation of transformers. Similarly, Sulfur, acids, carbon deposits, various gases, and sludge—which is primarily an oxidation product whose formation is mostly increased by temperature—form when the insulating oil in high voltage equipment is subjected to these mechanical, electrical, and thermal stresses during its operation. If the conducting impurities and moisture are higher, then the breakdown voltage will be observed lower in the transformer oil.

1.3 Motivation

The importance of testing and monitoring the dielectric strength of insulating liquids oil cannot be overstated, especially when it comes to the main electrical equipment such as transformers. The consequences of abandoning this essential aspect of maintenance are notable and far-reaching. Internal arcing or the total failure of equipment due to insufficient dielectric strength causes a severe risk of damage [17, 18]. Such unplanned and sudden breakdowns not only result in substantial commercial losses, but they also have the potential to cause devastating harm to human lives [19]. Addition to this, they can disastrously disrupt the reliability of the entire power system network, leading to widespread outages and blackouts causing economic and service repercussions. To save the power system from blackouts, understanding of the breakdown mechanisms of transformer insulating liquids is crucial, encompassing both AC uniform fields and divergent non-uniform fields subjected to AC and lightning impulse voltages [20]. These breakdown mechanisms are complicated and influenced by various internal and external factors. In uniform electric fields, dielectric strength is crucial to prevent breakdown, while in non-uniform fields, it becomes even more crucial as the stress on the insulating oil can vary significantly across different points within the equipment [21-24]. To make sure the safe and reliable working of transformers, it's important to consider these field influences while studying the breakdown mechanisms of transformer insulating mineral oil. By performing regular testing and monitoring of the oil dielectric strength, serious issues can be detected early, that allows for timely maintenance or replacement to be scheduled before catastrophic failures take place within the power system.

Testing the dielectric breakdown strength on a regular basis is a proactive measure that enhances the overall reliability of the power system and helps avoid power equipment breakdowns [25, 26]. It ensures that transformers and all other electrical equipment continue to function within safe bounds, minimizing risks to equipment and human life while enhancing the stability and efficiency of the power supply network. Insulation breakdowns may arise from pre-breakdown phenomena such as streamer discharges [27], which have the capacity to progress into full-path propagations. It is noteworthy that not every streamer will inevitably result in breakdowns; some may even extinguish or disappear during the propagation phase. Insulating oil in high voltage equipment is subjected to a variety of stress factors during operation, and monitoring its health and condition is critical to preserving the equipment's reliability. These electrical or thermal strains can cause various types of oil contamination [26], which can affect the dielectric characteristics and, as a result, the equipment's overall performance. In this section, several tests are carried out to acquire insight into the breakdown mechanisms of mineral oil in both AC uniform and divergent electric fields [28, 29]. Partial discharge (PD) in transformer insulating liquids has a substantial impact on insulation failure in power transformers. The Partial Discharge Inception Voltage (PDIV) is commonly employed to assess the partial discharge behavior of insulating liquids, following the IEC 61294 standard test procedure [30].

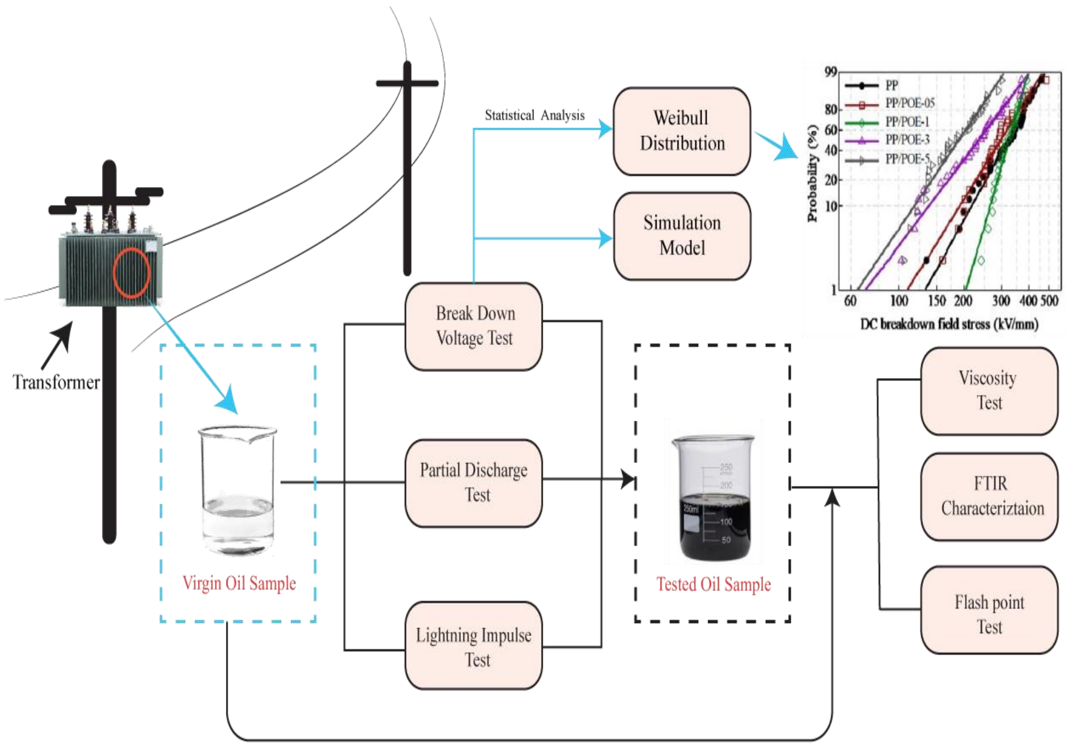


Figure 1.1: Schematic overview of the research plan

Hence, the motivation behind the study plan described was to explore influence of all potential electrode configurations on the breakdown mechanisms of insulating transformer oil under both uniform and highly divergent electric field conditions in order to minimize insulation failure. Additionally, investigating the behavior of partial discharge under various electrode geometries depicting all potential faults, as this is critical for accurate transformer health assessments. Understanding how electrical stresses contribute to contaminants in insulating oil under different electrode setups is essential for improving the reliability and safety of electrical equipment.

1.4 Problem Statement

Faults in the insulation, dielectric, and oil account for approximately 50% of transformer failure costs. The main problem in electrical power systems, particularly transformers, is to address difficulties and weaknesses in the insulating systems. Designing effective power equipment necessitates an understanding of the fundamental theoretical causes of oil breakdown, specifically the electric field conditions required for electron avalanche formation. Similarly, it is critical to understand the basic dynamics driving partial discharges that lead to liquids' entire breakdown. Every discharge event degrades materials due to the energy impact of high-energy electrons or accelerated ions. When organic insulating materials are exposed to partial discharge (PD) and breakdown voltage (BDV), they undergo physical erosion caused by streamers and charged particles resulting from electrical stress. This is accompanied by chemical deterioration in the oil as hydrocarbon molecules undergo bond breakage.

1.5 Objectives

- This study aims to examine how electric field homogeneity affects the breakdown of insulating oil in transformers.
- • Investigate how different voltage configurations, such as AC and full wave lighting impulse voltage, affect the breakdown mechanism.to analyze the behavior of partial discharge under all electrode configurations depicting the faults in oil.
- to assess oil quality degradation after exposure to electrical stress in terms of flash point and viscosity.
- to confirm breakdown voltage conformity across different setups, including AC, negative, and positive lightning impulse configurations through Weibull distribution.

1.6 Research Methodology

The detailed flow chart of research methodology explained as follows.

1. In this thesis, destructive electrical tests are performed on virgin oil samples. The test includes AC- breakdown voltage and lighting impulse breakdown voltage.

2. Non-destructive partial discharge test, physical-chemical property flash point and viscosity test performed on both virgin and electrically tested oil sample.
3. Characterization of both virgin and electrically tested oil samples is done with Fourier Transform Infrared Spectroscopy (FTIR).
4. The results were collected and analyzed.
5. A comparison was made between physical-chemical properties change of virgin and electrically tested oil sample.

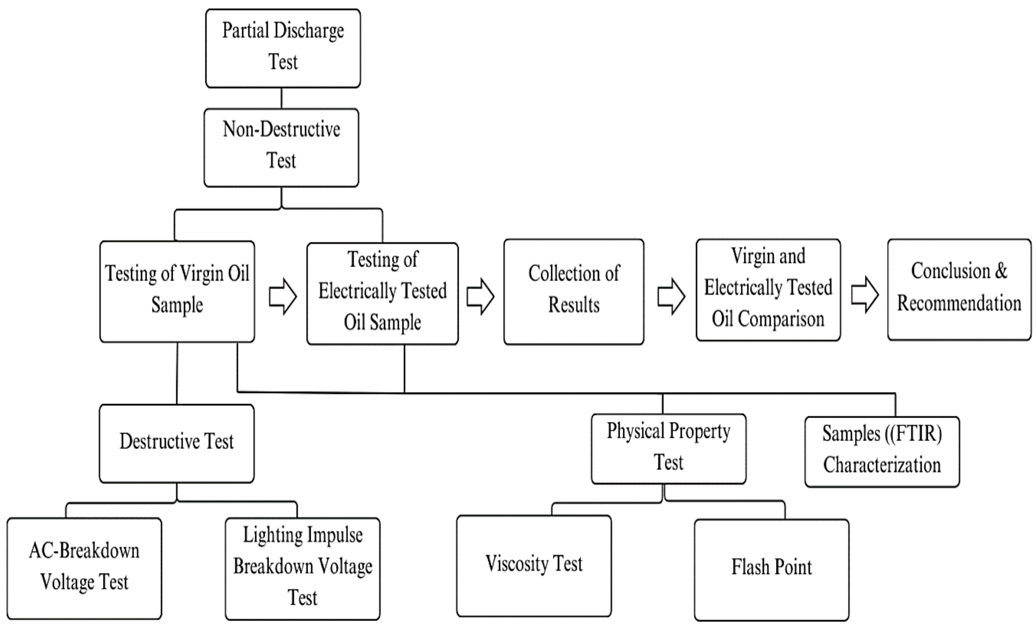


Figure1.2 : Flow Chart explaining Research Methodology

1.7 Research Gap

This thesis investigates chemical impurities in insulating oil due to electrical stresses, using six electrode configurations essential for practical diagnostic purposes. These configurations are critical for assessing insulation breakdown and equipment health, yet fundamental studies in this area remain limited and poorly understood. In transformer insulation research, the combined impact of various electrode configurations on insulating transformer oil breakdown mechanisms under different electric field conditions has not been thoroughly investigated. Urgent investigation is required to study partial discharge behavior under diverse electrode geometries, which represent all potential faults. Certain effects of contaminants on insulating oil properties following breakdown mechanisms under various electrode configurations must be evaluated before recommendation to the industry. Closing these research gaps would considerably increase our understanding of transformer insulation, and lead to higher reliability transformers.

1.8 Thesis Organization

Keeping in view the goals and tasks, this thesis has been organized in the order mentioned below.

Chapter 1:

This chapter presents the introduction, motivation, problem statement, objectives, methodology and research gap of this research work.

Chapter 2:

Mineral oil, which is frequently used in power transformers, is thoroughly examined in this chapter along with its breakdown mechanisms. The study delves into the behavior of mineral oil under several scenarios, encompassing both uniform and non-uniform electrical fields, as well as AC and lightning impulse voltage scenarios.

Chapter 3:

This chapter focuses on details of sample type; techniques used to analyze different properties of insulating transformer mineral oil. Experimental setup and procedure for partial discharge test, breakdown voltage test under AC and lighting impulse.

Chapter 4:

This chapter presents detailed results and statistical Weibull analysis of breakdown voltage tests for various electrical field configurations under AC voltage. It also compares the oil quality degradation using Fourier Transform Infrared Spectroscopy (FTIR), Partial discharge, viscosity, and flash point tests between virgin and electrically tested mineral oil subjected to AC breakdown voltage stress.

Chapter 5:

This chapter presents comprehensive results and statistical Weibull analysis of breakdown voltage tests conducted under lightning impulse voltage for various electrical field configurations. Additionally, it evaluates oil quality degradation through comparative analysis of Fourier Transform Infrared Spectroscopy (FTIR) and viscosity measurements, comparing virgin and electrically tested mineral oil subjected to lightning impulse (LI-BDV) stress.

Chapter 6:

This chapter describes the conclusion and future work after this research work.

Summary

This chapter discussed the overview of transformer insulating mineral oil breakdown. The insulation strength of mineral oil can deteriorate due to various factors and can cause transformer failure before time. It is important to consider faults and conditions that degrade the properties of insulating oil. To prevent unanticipated transformer failures, reliable insulating design and early identification of PD faults are essential. Both necessitate a deep comprehension of transformer insulating liquids' PD and breakdown properties of insulation system under various conditions. The chapter further included motivation, problem statement, objectives, and novelty of this research work.

CHAPTER 2: LITERATURE REVIEW

2.1 Background

The breakdown mechanism of insulating liquids is discussed at the start of this chapter, with a focus on mineral oil. The breakdown mechanisms for both AC and lightning impulse voltage scenarios will then be explored, along with uniform and non-uniform divergent fields. The purpose is to present a comprehensive review of the research breakthroughs made in understanding breakdown mechanisms in transformer liquids over the last century by selecting noteworthy experimental data from a wide variety of literature.

Power transformers are indispensable components of electrical networks, ensuring the efficient transmission and distribution of electrical energy. For many years, mineral oil has served as the preferred insulating medium in power transformers due to its exceptional dielectric properties. However, during operation, power transformers are subjected to various electrical stresses, particularly from alternating current (AC) and lightning impulse (LI) voltage. These stresses can lead to breakdown or electrical partial discharges in the mineral oil. Understanding the breakdown mechanisms is imperative as these failures can result in severe consequences such as equipment damage, operational disruptions, and even power outages.

The breakdown voltage of insulation, a critical aspect of the system, directly influences the security, reliability, and efficiency of electrical systems and equipment. It is essential to comprehend this parameter and ensure that insulation operates well below its breakdown voltage to mitigate the risks of electrical failures. Routine testing, maintenance, and a comprehensive understanding of fault possibilities and the partial discharge leading to the breakdown phenomenon are crucial for determining and maintaining the integrity of electrical insulation.

Extensive research has been conducted on pre-breakdown partial discharge and breakdown phenomena in insulating liquids under various concerning parameters. It is well-established that breakdown manifests distinct mechanisms under uniform fields and non-uniform fields. Additionally, uniform and non-uniform fields have significant effects, along with other parameters, on the breakdown strength in mineral oil.

2.2 Partial Discharge Fundamentals

According to IEC definitions, a partial discharge is "a localized electrical discharge that may or may not occur adjacent to a conductor, only partially bridging the insulation between conductors" [31]. The electric field intensity that causes these discharges happens when it surpasses the tolerance limit of the insulating material. These zones can be located anywhere away from the electric field source or conductor. The difference between breakdown and partial discharge must be understood; breakdown includes the creation of a conducting channel connecting all of the electrodes, whereas partial discharge is restricted to a section of the insulating material [32, 33]. During a partial discharge (PD), many types of energy are exchanged, including current, mechanical waves, electromagnetic waves, and chemical processes. These occurrences serve as the foundation for the measurement and detection of Parkinson disease. PD can occur as an internal discharge within a solid or liquid dielectric, a surface discharge at a dielectric contact, or a corona discharge in a gaseous dielectric. The main focus of this study is PD in transformer fluid.

Any dielectric liquid will experience liquid discharges in its gas phase [34–36]. Before discharges, gas bubbles may exist, or they may form during liquid processes such evaporation, vaporization, or electrolysis when under electrical stress [37–39]. The movement of conducting particles, cavitation, and electrodynamic motion are the main causes of PD in liquids [39, 40]. When using needle electrode designs like needle-to-plane or needle-to-sphere electrodes, partial discharge (PD) is typically started in a laboratory setting. The polarity of the voltages applied across the electrode system changes when there is an AC stress. The PD that is started at the needle tip can therefore be either positive or negative, depending on how the voltage potential of the needle electrode matches the polarity of the opposing electrodes.

2.2.1 PD Equivalent Circuit

Discharges are always initiated in gas-filled cavities or air bubbles within the liquid because a cavity has a lower dielectric strength than the surrounding liquid and is prone to amplified field gradients due to its permittivity and form. Figure 2.1 depicts a basic three-capacitor circuit that simulates the charging and discharging operations within a liquid. The symbol Vs indicates the voltage across the liquid sample. The capacitance Cc represents a void or gap. The greater capacitance Cb in series with Cc reflects the liquid component that is subjected to the same electric flux as the cavity or void. The parallel capacitance Ca represents the remaining liquid. According to Reference [32], the capacitances satisfy the

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

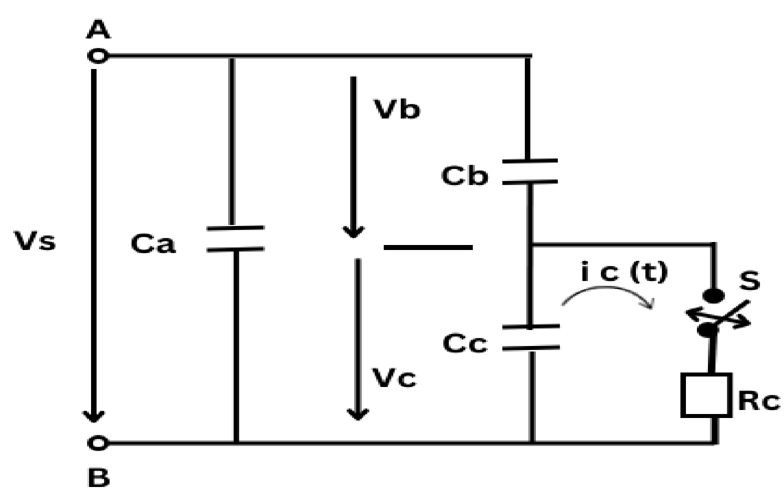


Figure 2.1. Equivalent circuit of PD

The real charge delivered to the liquid from the PD site (the gas-filled cavity Cc) is denoted by ΔQc. It is impossible to measure this charge quantity since the C_c terminals are inaccessible. The terminals of the Ca are accessible. This implies that it is possible to detect the voltage drop across Ca, which corresponds to ΔVc by

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

In addition to apparent charge, PD current pulses can be characterized by a wide range of additional measurements or derivatives [36]. The following lists the definitions of four chosen quantities:

i. Pulse number: The total number of pulses detected in a certain period of time is called the pulse number.
ii. Pulse repetition rate: This measure, which is commonly expressed in terms of numbers per minute, is the proportion of pulses to time interval length. If the recording period is set to one minute, the pulse number and pulse repetition rate will be numerically comparable.
iii. Phase angle: A pulse that is pulsed (PD) has a phase angle that is determined by the applied AC voltage phase angle at the exact moment the pulse occurs. Its location falls between 0° and 360°. Since both the applied voltage and the PD pulses are time-dependent, phase-resolved partial discharge, or PRPD, patterns are usually produced by combining the two.

2.3 PD Patterns

In addition to showing data in PD patterns, digital PD measurement equipment may measure apparent charge, phase angle, and PD occurrence number/frequency over a preset detection period. In this field's preliminary research, plotting the PD amplitude vs the number of PDs revealed information on the PDAD (PD amplitude distribution) of an insulating liquid. The PD behavior of an insulating liquid can be determined, and PDIV can be estimated, by comparing PDADs generated at different voltages [41–43]. Because larger PDs occur, the range of PD amplitude in a PDAD grows as the applied voltage increases [44].

Phase resolved PD (PRPD), the PD pattern that is currently most frequently used in PD measurements, is shown in Figure 2.2. A PD pattern has asymmetric positive and negative discharges. Since negative PD current is composed of short-duration pulses without a discernible DC component, positive discharges frequently have a higher PD magnitude than negative discharges under divergent AC stress [45].In much of the research employing needle-to-plane or needle-to-sphere electrode systems, as depicted in Figure 2.2 [46], the PD magnitude of a liquid at a certain voltage is linked to the largest positive PD. Positive discharges are larger than negative discharges, however they may not occur as frequently. PRPD patterns are an easy technique to assess the magnitude and phase angle distribution of discharges while also providing information on the discharges' time-domain relationships. 2D PRPD patterns, or Φ-Q PD patterns, show PD magnitudes as a function of phase angle. Positive and negative discharges are not equal in a PD pattern. Positive discharges often have a larger peak discharge current (PD) amplitude than negative discharges under divergent AC stress [45], owing to the fact that negative PD currents are composed of brief pulses with no evident DC component. The majority of studies using needle-to-plane or needle-to-sphere electrode configurations relates a liquid's PD magnitude to its maximal positive PD. Compared to negative discharges, positive discharges are bigger but may not be more frequent. The literature indicates that the liquid type, the needle electrode's tip radius, and the sensitivity of the measurement equipment are related to the voltage polarity that produces the most discharges [44, 47, 48]. However, distinct counts become more helpful when examining the mechanisms behind the occurrence of PD under each polarity. The phase angle range in which PDs occur varies with applied voltage, much like the PD magnitude and number. As the voltage rises, PDs happen over a larger phase angle range [49].

Though they might not happen as frequently, positive discharges are greater than negative discharges. The literature indicates that the voltage polarity that results in the greatest number of discharges is related to the liquid type, needle electrode tip radius, and measurement equipment sensitivity [44, 47, 48]. Distinct counts, however, are more suited for examining the causes behind each polarity's unique prevalence of Parkinson's disease. The amplitude, quantity, and phase angle range of phase dips (PDs) vary with applied voltage. PDs happen over a larger phase angle range as the voltage rises [49].

2.4 Introduction to Breakdown Mechanisms in Mineral Oil

When electrodes submerged in a dielectric liquid are exposed to a high enough voltage, electric breakdown takes place. Streamers initially emerge and expand each time the liquid breaks down [9]. Pure insulating oil always contains some free electrons that, when subjected to intense electrical stress, dissociate and promote the growth of streamers. The electric field causes these electrons to be affected and dissociated, which ultimately causes the insulating oil to break down. Streamers are always initiated near the needle tip, sharp disc edges, and irregular electrode surfaces because their beginning is dependent on the electric field [50]. The anode or cathode of the electrode is where positive and negative streamers are initiated, respectively. A micrometer-sized gaseous phase appears as illustrated in Figure 2.2 in the liquid phase with the onset of positive streamers, and a brief

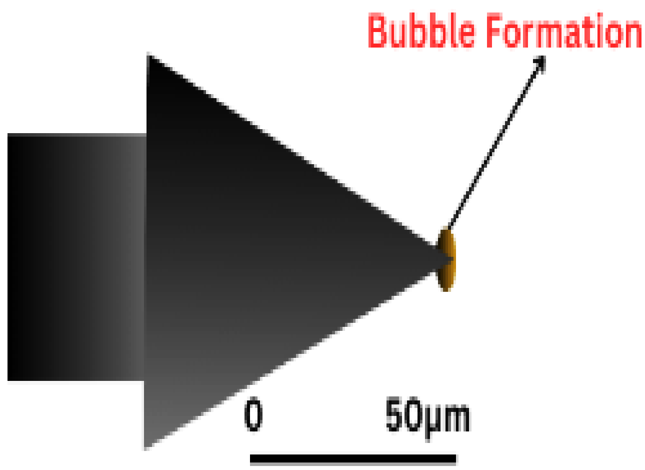


Figure 2.2: Bubble generation near a sharp tip of needle electrode in a transformer dielectric oil (needle tip radius = 3 µm; voltage applied = 16 kV; modified image is given here; the original image is presented in [23])

electric current and light emission are observed [51, 52]. On the other hand, negative streamers in dielectric liquids are preceded by light emission and an electric current pulse, and after a few nanoseconds, a small bubble forms at the cathode [50, 51, 53-55].

Based on their characteristics, positive and negative streamers are separated into "modes" (e.g., form, propagation velocity, intensity of light emitted). Various electrode configurations are used to examine the streamers' behavior[50, 52, 53]. There are two types of mineral oil failures that occur when AC voltage is applied: "direct" breakdown and "burst" breakdown [56]. A single streamer during an AC cycle causes a "direct" failure, whereas several streamers occurring during multiple cycles induce a "burst" collapse. Engineering uses insulating oil, which is inherently impure and contains a variety of contaminants. Impurities such as free water, dissolved water, or particles with higher electrical conductivity and permittivity than the oil will form a conductive bridge in the presence of an electric field (voltage), lowering the oil's breakdown voltage value. The following factors influence the breakdown voltage of transformer insulating oil.

2.4.1 Influence of Electrode Material

The impact of electrodes on the breakdown strength of insulating liquids may be analyzed from two angles: electrode material and electrode scale, which comprises electrode area and gap distance [57]. The rapid beginning of a breakdown through localized field augmentation is primarily to blame for this decline. To attain larger breakdown strengths, transformer designers usually use transformer boards to split large oil gaps into smaller oil gaps of a few millimeters [58]. This demonstrated that the electrode's impact on the insulating qualities of oil was real. It is commonly known that the insulating oil's breakdown strength is influenced by the electrode material used in breakdown test measurements. Subsequent investigation using DC voltage and lighting impulse showed that the insulating liquid strength dependent [59]. One theory proposes that electrons emitted from an electrode could start the breakdown of clean, well-treated oil [60]. The natural oxide layer that forms on the cathode surface can act as an effective barrier to electron emission and neutralization. This could consequently have an effect on the liquid's dielectric strength. In contaminated insulating mineral oil, the electrode material has less of an impact on the breakdown strength measurement than in clean oil.

2.4.2 Influence of Electrode Scale

There are two components to the electrode scale effect: the electrode area effect and the electrode gap distance effect. It is commonly known that the breakdown strength tends to decrease with increasing electrode scale [61, 62]. In general, when electrode area (or electrode area effect) and gap distance rise, insulating liquids' dielectric strengths decrease as depicted in Figure 2.3 [63, 64].

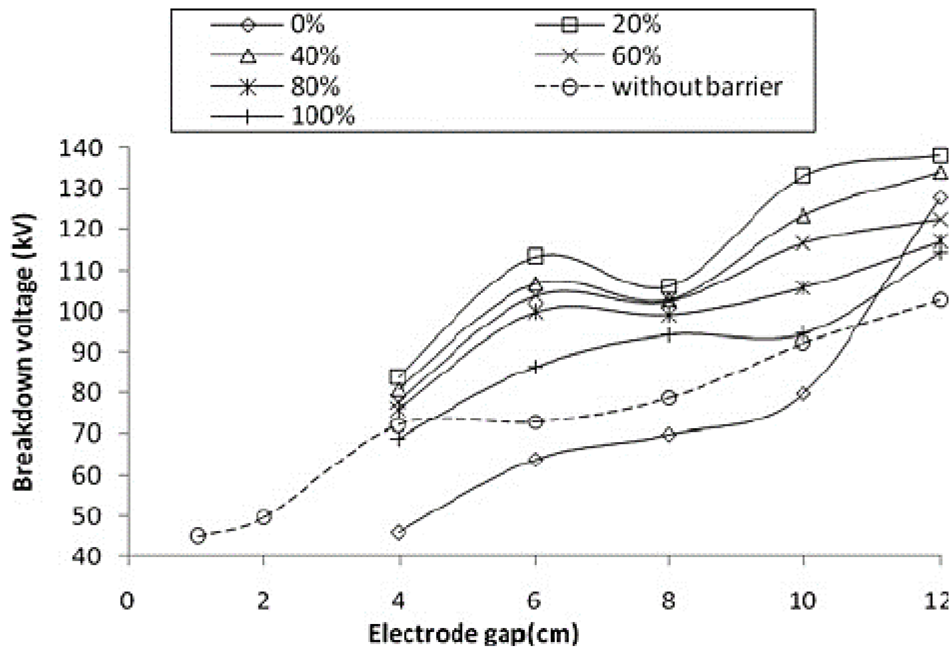


Figure 2.3: Typical relationship between AC breakdown voltage and the electrode gap scale [34].

These negative effects, also known as the volume effect or scale effect, were noted for most investigations, and were related to both electrode area and gap distance Due to the fact that the distribution of breakdown strength for mineral oil in regular fields more closely matches the Weibull distribution than the normal distribution [50]. Dielectric strength decreased as a result of the weakest connections contributing to the liquid breakdown caused by the expansion of the liquid scale under stress from the electric field. However, significantly different results were obtained [63, 65, 66], showing that the dielectric strengths of liquid tests conducted in uniform fields were unaffected by the gap distance between the electrodes. Therefore, when electrode area increased more than gap distance, liquid strengths decreased more sharply.

2.4.3 Influence of Particles

Transformer particles originate from a variety of sources [67]. Particles that are stuck to the walls or the winding surfaces of the transformer tank during the manufacturing process are left behind. Even though the oil that is put into transformers is often filtered to remove contaminants, the leftover particles may contaminate the refined oil again. Therefore, before a transformer is put through standard factory testing, it must go through a numerous filtering process [68]. Routine inspections involving the removal of lids and coverings introduce dust and other environmental contaminants into the transformer liquid while it is operating. Throughout the transformer aging process, the cellulose materials in in-service transformers continuously release particles into the liquid. According to the CIGRE report [69], field transformer failures are typically associated with elevated particle contamination levels. Experimental studies have elucidated the essential role that particles play in the process of electrical breakdown in insulating liquids. In uniform fields, there is a strong relationship between particle mobility and the mineral oil breakdown process. Because of the local field's amplification, partial discharges can happen when charged particles—especially metallic ones—come into touch with high voltage electrodes.

The dielectric strength of mineral oil under AC voltage is essentially unaffected by a small number of particle contaminations in divergent fields [38]. Particles travel along the field lines in divergent fields because they are charged by space charges. The point electrode gradually becomes surrounded by regions of maximum field strength where these particles are aggregated, essentially expanding the electrode tip's radius [70].

2.4.4 Influence of Gas and Moisture

Water has a considerable impact on transformer oil's AC breakdown strength. Moisture is a sensitive element that impacts the breakdown voltage (71). Water molecules' polar nature allows them to easily elongate and organize in the direction of the electric field. A conductive "bridge" between the two poles may emerge as a result, significantly lowering the breakdown voltage [72]. In addition to the amount of water present, the state of the water in the oil influences the breakdown voltage size. Emulsified water often has a greater impact on breakdown voltage than dissolved water [73, 74].

There are various sources for transformer liquid gas [75]. The gas may be absorbed from the atmosphere as air or as a hydrocarbon. Gas bubbles appear in the transformer liquid when the saturation point is reached. Mineral oil's dielectric strength is significantly harmed by the presence of gas. The dependence of the mineral's dielectric strength serves as an indirect proof of this harmful effect [76].

The following is a review of several previous studies that were conducted on mineral oil under various experimental conditions, including gap spacing, temperature, electrode arrangements, polarity and wave form of impulse voltages, AC and DC voltages, and insulation systems (in liquid).

2.5 Breakdown Mechanisms under AC and Lightning Impulse Voltage

Waveforms of AC voltage are commonly used to measure the dielectric strength [77–81]. Lightning strikes and other electrical stressors can cause impulsive overvoltage in power transformers. Therefore, dielectric strength is tested using lightning impulse voltage waveforms in a number of studies [37, 50, 60, 65, 67, 79-83]. To gain more insight into the insulating properties of electrode shape uniformity, partial discharges are also measured. Comparatively speaking to impulsive voltage, however, fewer studies have been carried out to examine the breakdown mechanism in mineral oil under AC voltage [56, 84, 85].

Despite their similarities, the breakdown streamer behaviors under impulse voltage and AC voltage differ significantly. Compared to impulse test findings, AC breakdown voltages are more sensitive to oil impurities. Despite their similarities, the breakdown streamer behaviors under impulse voltage and AC voltage differ significantly. Compared to impulse test findings, AC breakdown voltages are more sensitive to oil impurities. An additional distinction is that the impulse strength is less than the AC breakdown strength for both positive and negative polarities. The variance could be attributed to changes in voltage waveforms and electric field distributions used in each test.

For many different reasons, breakdowns, streamers, and incomplete discharges are investigated under various electrode configurations and test scenarios. Semi-spherical electrode designs are often used to analyze AC breakdown in compliance with ASTM D1816 or IEC 60156 standards [37, 40, 58, 66, 85-88]. Similar to this, standards like ASTM D3300 and IEC 60897 are used to determine the impulse breakdown voltage of mineral oil using the needle-sphere electrode setup [66, 82, 89-92]. Additionally, needle-plane electrode designs are used to measure partial discharges, streamer properties, and other unconventional tests [31, 32, 37, 49, 52, 68, 73, 75, 80, 90].

Experimental studies have used a variety of electrode materials, including brass [66, 82, 86, 89, 91-95], copper [92], stainless steel [65], steel [82, 96], and tungsten [65, 76, 80, 89]. The longer the duration of AC voltage compared to impulsive voltage, the more space charge accumulates in the mineral oil that insulates transformers, influencing failure behavior. This is related to the cavities that form around the point electrode during initiation, as well as the ionized material inside the "streamer channel" during propagation. When a gaseous bubble generated at the channel tip interacts with an existing streamer channel, the latter expands.

Under AC voltage, mineral oil typically has two types of streamer channels: weakly conducting and considerably conducting (leader) [97]. Strongly conducting streamer channels appear only at voltages close to the breakdown voltage. A little hole around the extremely stretched electrode gives streamer starts their distinct appearance. Pre-initiation is demonstrated by the electrode delivering a brief current pulse into the liquid. Positive voltage significantly increases the electric field around the pointed anode tip, potentially ionizing the liquid molecules in front of it. As a new tip, the anode absorbs electrons and emits positive charges. This process continues until the field intensity at the tip is sufficient to ionize liquid molecules.

It is purposely left with positive charges in the bulk liquid to maintain a high field close to the streamer tip [81]. This demonstrates that positive streamers are naturally electrical. Positive streamers need a strong electric field to originate, and this field affects the inception voltage of the streamer. Power transformer insulation design is influenced by the lightning impulse strength of insulating liquids since the lightning impulse test is a common manufacturing test for high voltage power transformers. The insulating liquids' further intrinsic qualities can be discovered through electrical testing with lightning impulses..

2.6 Breakdown Mechanisms in Uniform and Non-Uniform Divergent Fields Case

Divergent and uniform fields share a common breakdown mechanism, albeit a variety of factors can influence liquid breakdowns [31, 32, 35, 37, 40-42, 46, 62, 63, 67, 69, 73, 75, 76, 80, 82, 83, 91, 92, 96, 28-99]. A breakdown event occurs when the streamer completely fills the liquid gap, triggering the development of both. In uniform fields, maintaining dielectric strength is critical for avoiding breakdowns. This need is especially important in non-uniform fields, where the load on the insulating oil might vary considerably at different locations inside the device. However, the breakdown mechanisms in uniform and non-uniform diverging fields change due to differences in field conditions.

In uniform fields with a high average electric field, practically every streamer results in an electrical breakdown. As a result, the breakdown voltage is highly related to the streamer initiation voltage, demonstrating that streamer initiation regulates liquid breakdown [100]. Because the average field in uniform fields is so weak, breakdown voltage levels are far higher than in divergent fields, where liquid breakdown is controlled by streamer propagation.

The streamer initiation field in clean oil is smaller than the lightning impulse voltage in uniform electric fields, and it may be comparable to the breakdown field under AC voltage. The extended duration of voltage application, which increases the likelihood of streamer initiation at lower voltage levels, can be used to explain this behavior. The streamer inception voltage is higher in contaminated oil [62, 101].

Since the streamer character of liquid breakdowns was established, extensive study has been conducted on breakdown behavior in diverging field conditions using disc electrodes or pointed needle tips. The majority of studies used a substantially divergent field and impulse voltage because breakdown streamer events are predictable, which is useful for oscilloscopic and photographic recordings [101–103]. Another method enabled by the use of impulse voltage is the investigation of streamer propagation at overvoltage in divergent fields [84,104].

Summary

This chapter begins with an introduction of the history of breakdown theory, followed by a review of the literature on the breakdown process in both uniform and divergent areas. It also discusses the features of partial discharge (PD) in liquids and how applied voltage and electrode geometry influence these characteristics. The liquid's composition—water, gas, particle, and additive content—has a significant impact on when breakdown occurs. As a result, unless the oil quality is scrupulously maintained to a comparable degree, comparing transformer liquid properties using breakdown tests in a homogeneous field is impossible. The breakdown strength in a uniform field is crucial when using transformer liquid at high voltage, particularly in high voltage transformers when the electric field is extremely weak and the stressed oil surface/volume is rather large. The beginning of the streamer is determined by the increased field strength around the point electrode in diverging fields, which is independent of the quality of the liquid. Liquid breakdown is determined by streamer propagation; however, not all streamers are responsible for breakdown. The AC breakdown voltage of transformer liquid is therefore significantly larger than the breakdown inception voltage under divergent fields.

CHAPTER 3: EXPERIMENTAL METHOD, SETUP AND TECHNIQUES

3.1 Introduction\

The purpose of this experimental investigation is to compare the breakdown voltages of mineral oil transformer insulators at low failure rates (i.e., withstand voltage) and to analyze the breakdown voltage of these insulators when subjected to AC and impulsive voltages. This requires regular checks on the quality of transformer fluid. Appropriate tests were undertaken to determine how electrical stressors affected oil quality.

3.2 Samples

This study involves the evaluation of virgin mineral transformer oil subjected to breakdown voltage testing under variant electric field conditions. Transformer oil has a high affinity for moisture absorption. This research aims to find any chemical and structural change in the oil molecules caused by repeated exposure to high voltage.

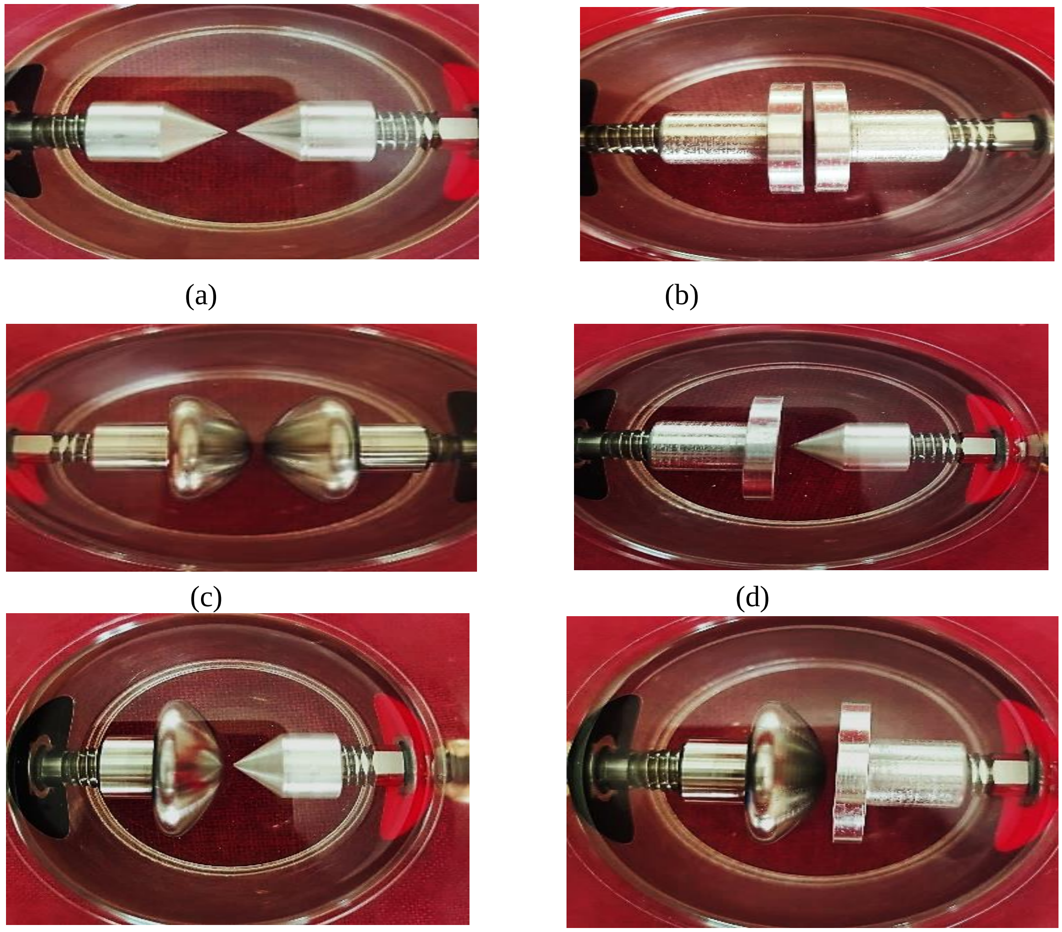
(a) (b)

Figure 3.1: (a) Virgin Transformer oil sample (b) Electrically Tested oil sample

Each oil sample underwent a minimum of 10 electrical AC breakdown, 20 electrical lighting impulse events and experienced partial discharges of up to 20. These tests utilized sinusoidal and impulse test voltages and a standardized electrode setup. During the breakdown voltage tests, sparking occurred, leading to carbonization and contamination of the oil referred to as electrically tested oil sample illustrated in Figure 3.1.

3.3 Electrodes Configuration

Sharp edges, whether in the form of conducting particles in power equipment or present due to electrode geometry, can create high field regions making them susceptible to partial discharge and breakdown voltage activities. To depicts these faults in this experimental approach, six different electrode configurations are used, showed in Figure 3.2.



(a) (b) (c) (d) (e) (f)

Figure 3.2: Uniform and Non-uniform Electric Field Configurations. (a) Needle- Needle (b) Plane- Plane (c) Hemisphere- Hemisphere (d) Hemisphere-Needle (e) Plane-Needle (f) Hemisphere-Plane

These configurations included hemispheric geometry as part of the laboratory equipment and other geometry like needle (tip radius 0.005μm) and plan electrodes, which were fabricated separately in turning workshop following IEC-60156 standard. When comparing the liquids under the different configurations, interesting results have been obtained for the AC and LI voltage setups. Dimensions of each electrode is shown in Figure 3.3.

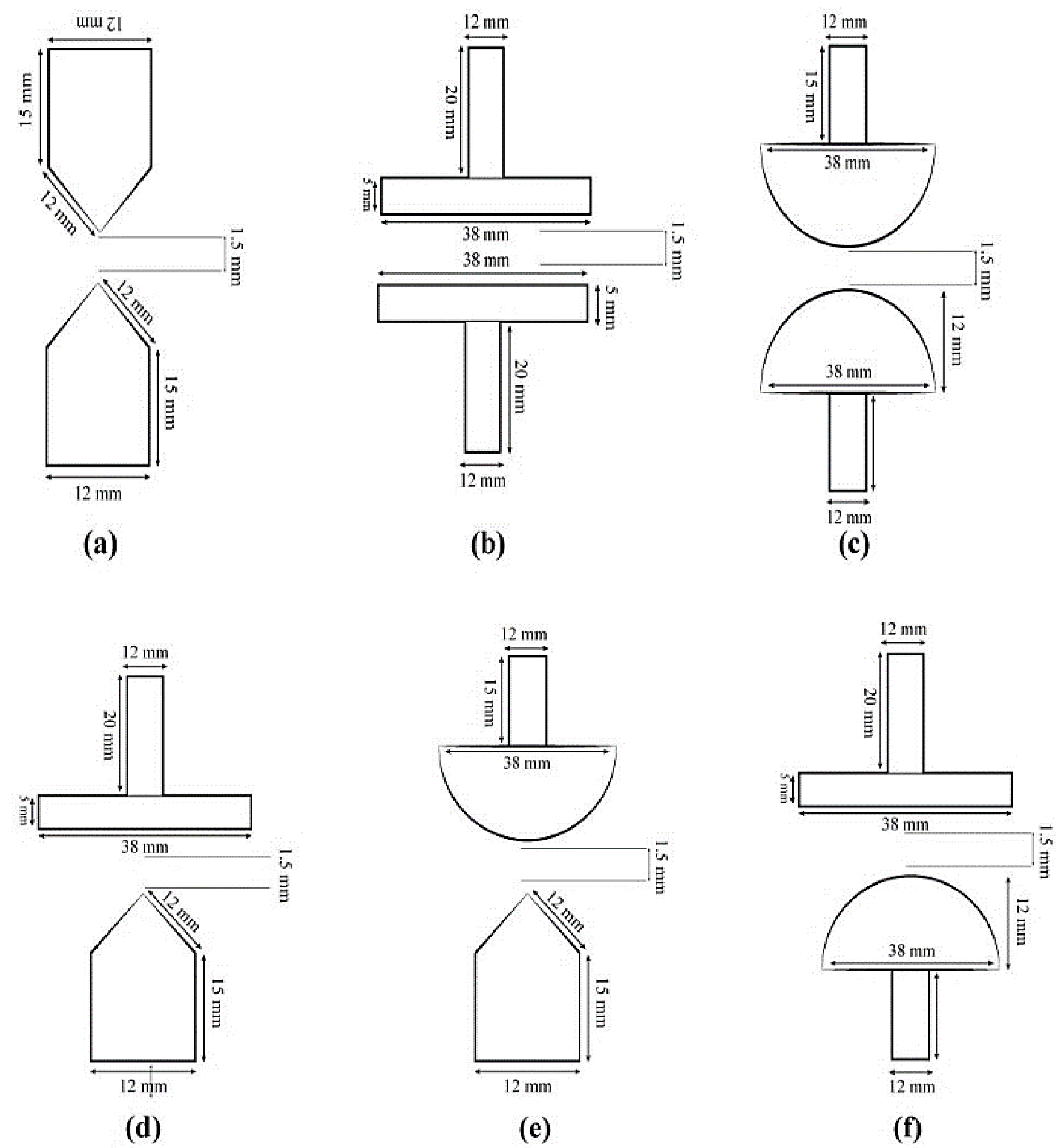


Figure 3.3: Dimensions of electrodes

3.4 Dielectric Properties Analysis Techniques

3.4.1 AC breakdown voltage

The insulation dielectric strength of electrical equipment insulating oil is evaluated through the Breakdown Voltage (BDV) test. When voltage is applied, the current passing through insulating oil rises abruptly, leading the oil to lose its natural insulating properties and turn into a conductor. This is referred to as insulating oil breakdown. The BDV test evaluates the oil's ability to withstand electrical stress, decreasing risks and preserving the longevity and safety of electrical systems while identifying potential issues early. The breakdown voltage test (BDV test) can be used to:

i. Estimate the transformer's remaining life.
ii. Boost operational safety.
iii. Avoid equipment fires.
iv. Assurance of transformer dependability
v. Predicting the remaining life of the transformer

3.4.2 Lighting Impulse Test

A lightning impulse test is performed on electrical equipment to ensure its insulation can withstand external lightning strikes during its operational life. Laboratories simulate high-voltage surges resembling lightning, called high-voltage impulses, for testing the insulation's resilience.

3.4.3 Partial Discharge Test

Partial discharge testing, or PD testing, is conducted to evaluate the health of electrical insulation. PD occurs when a section of an insulation system cannot withstand the applied electrical field, leading to a localized flashover. However, the overall insulation system can still endure the applied field. PD happens when the electric field across a void surpasses the PD breakdown threshold, which can be described as:

$$E_{void} = E_1 > \text{PD breakdown}$$

In this relation, the electric field across the void (E_{void}) must be greater than the PD breakdown threshold (E_1) for partial discharge to occur.

3.4.4 Fourier Transform Infrared (FTIR) Spectroscopy

For oil analysis, Fourier-transform infrared (FTIR) spectroscopy is a straightforward method. It is particularly helpful in identifying additives, dilution, and deterioration in different types of oils. It is also capable of simultaneously detecting many parameters, such as water, soot, gasoline, glycol, oil oxidation, antioxidants, and specialty additives. Molecules absorb infrared energy at particular wavelengths when they are exposed to it. Over time, low electrical discharges can alter the composition of oil, which can have an impact on its structure and functionality.

3.4.5 Viscosity Test

To measure the level of viscosity of both virgin and electrically tested transformer oil, a viscosity test was performed. In this experimental test, viscosity values at various temperatures and shear rates are obtained using the standard ASTM D445 test method and a measuring instrument known as the Brookfield viscometer. It's important to note that lower viscosity indicates better heat dissipation efficiency, especially in the case of transformer insulating liquids. Shear stress can be defined as viscosity times shear rate. Therefore, the viscosity is equal to shear stress divided by shear rate. The kinematic viscosity ($mm^2 \cdot s^{-1}$) is commonly determined by using the following formula:

$$V = C \times t$$

V = kinematic viscosity (mm^2/s)

C = viscometer constant (mm^2/s^2)

t = time (s)

3.4.6 Flash Point Test

To determine whether the transformer insulating liquid in this study is prone to ignition when exposed to fire at a specific temperature, a flash point test is conducted following the ASTM D1655 standard test method. Both virgin and electrically tested transformer oil samples are subjected to the flash point test using a Sung Seta Flash Series 3 flash point tester.

3.5 Experimental Setup and Procedure

An experimental setup for AC and lighting impulse voltage was established to study the effect of voltage types and electrode configurations on insulating mineral oil.

3.5.1 AC Breakdown Voltage

Power frequency and breakdown voltage measurements on transformer oil are performed in accordance with the IEC 60156 standards and protocols stated in the preceding work. The breakdown voltage is measured using a 500 ml test cell and an oil test kit with hemisphere, needle, and plane disc electrodes. A 100ρF capacitor is utilized in parallel to measure BDV, while a 2.4 kΩ current limiter resistor controls the amount of current.

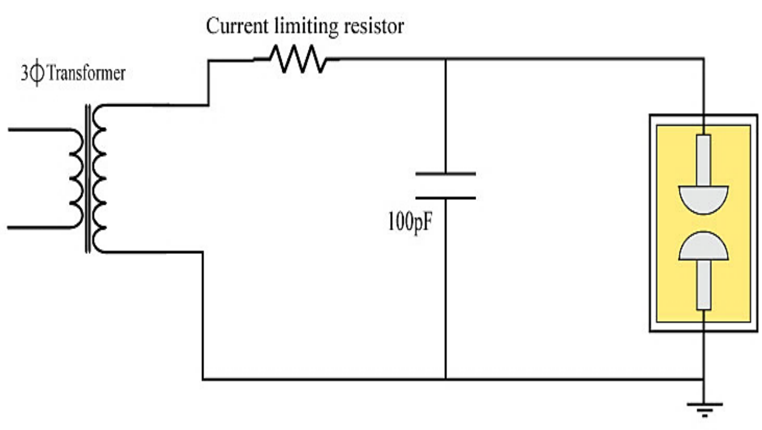


Figure 3.4: Schematic diagram of oil BDV testing kit.

In accordance with the standard, maintaining the cleanliness of the test cell is crucial when measuring dielectric properties due to the high susceptibility of insulating liquids to contamination.

Before usage, the test cell must be thoroughly cleaned with a volatile solvent, and the electrode distance should be precisely set at 1.5 ± 0.5 mm. Although electrodes gap value at distance of 1.5mm for AC and LI is not valid for transformer design purposes but they are useful to provide necessary information for transformer insulating oil behavior under different electric field configurations. Up until breakdown, the voltage was continually delivered to the electrodes at a constant increase rate of 2.0 ± 0.2 kV/s. Five minutes must pass between two measurements for the liquid to maintain the characteristics listed below in Table 3.1.

Table 3.1: Physicochemical properties of mineral oil

Property	**Transformer oil**
Density at 20 °C	0.849
Kinematic viscosity at 40 °C (cSt)	9.5
viscosity at -20°C (mm^2/s)	301.50
Pour point (°C)	-39.4
Flash point (°C)	140.0
Fire point (°C)	167
Total acid number (mg KOH/g)	<0.005
Antioxidant content	<0.3%
Water content (mg/kg)	8.31
Gassing characteristics (mm^3 /min)	-35 to +30
Interfacial tension (mN/m)	61.0
Resistivity (Ω.m)	234.10
PCA content	0.69
Dissipation factor at 90 °C	0.00196
Sludge	0.0671
DDF at 90°C	0.00310

An oil sample from the virgin transformer oil tank is collected. The test voltage collapses as current rises because of breakdown in an electric arc. The test voltage is shut off immediately as soon as the arc ignites. It is essential to turn it off extremely quickly because the amount of energy that is introduced into the oil and is burning it during the breakdown must be kept low to minimize the additional pollution caused by carbonization. At the exact moment of the breakdown, the test voltage's root square value is measured and reported as the breakdown voltage.

3.5.2 Lighting Impulse Test

The main tools utilized in this test to produce lightning impulses are the LGR 100–20 charging rectifier and the Haefely impulse generator, model number SGSA 400–20. A non-inverting impulse Marx generator circuit, capable of producing 100 kV per stage, is used by the system. This configuration generates typical lightning impulses with a pulse shape of 1.2/50 µs and permits a maximum output voltage of 400 kV. To regulate and control the

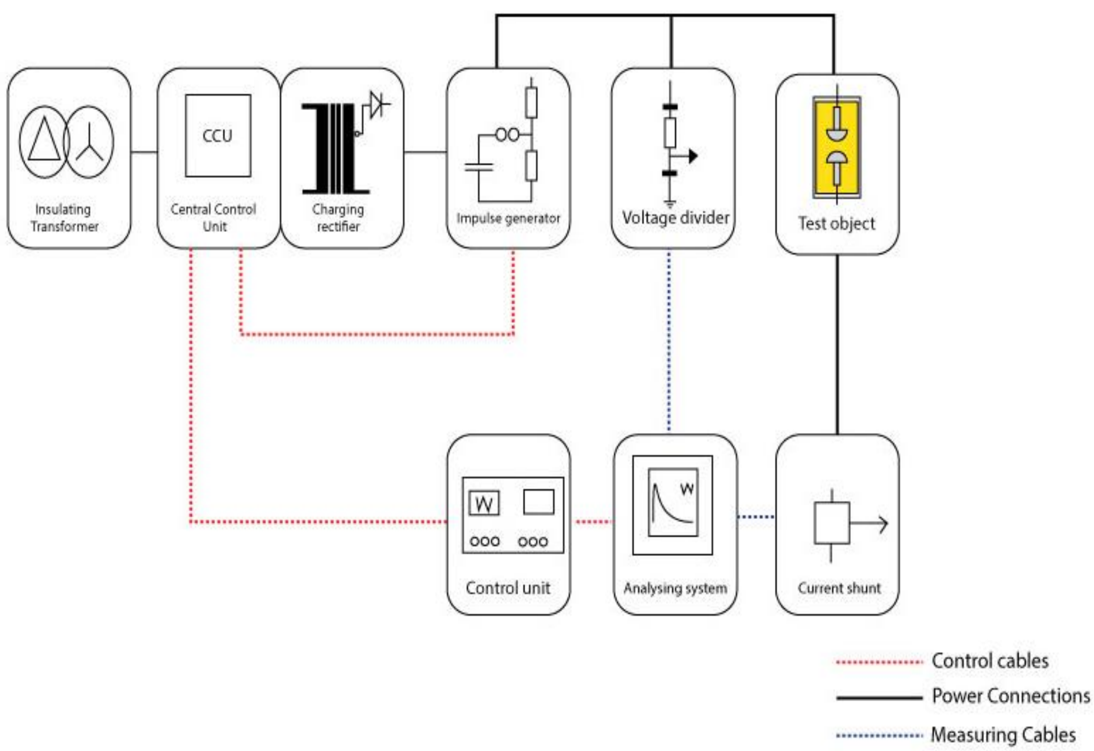


Figure3.5: Schematic of lighting impulse setup

output of the lightning impulse generator, a control device known as the Impulse Generator Control Type GC 257 is utilized. This control unit ensures precise management of the lightning impulse parameters.

For each configuration included in this study a set of 20 measures of positive and negative lighting impulse breakdown voltage was carried out. The breakdown voltage (BDV) testing procedure for insulating liquids involves several key steps. Firstly, a test cell is filled with 500 ml with oil, and a resting period of ten minutes is allowed for sample stabilization. Then, impulses are applied with an initial voltage level set 5 kV below the expected breakdown level. This process is repeated three times to assess the liquid's dielectric strength. If no breakdown occurs during the initial three measurements, the voltage is increased 5kV at each step, with a minimum 30-second interval between tests.

Upon the occurrence of the first breakdown, the applied voltage is reduced by 5%, and three impulses are applied at this new level. If any of these three impulses results in a breakdown, the voltage for the subsequent impulse is decreased by 5%. This iterative process continues, with voltage adjustments, until a total of ten breakdowns are recorded. "No-breakdown events" represent the sum of test trials that do not result in a breakdown. These trials are considered successful in maintaining equipment integrity without failure. This counting method helps in assessing and analyzing the performance and reliability of the equipment under test.

$$k = \sum \text{ki},$$

$$q = \sum \text{qi},$$

where: ki – tests resulting in a breakdown, qi – tests without a breakdown.

3.5.3 Partial Discharge Test

Partial discharges in liquid dielectrics occur within void cavities, typically formed at stress enhancement sites like sharp metallic edges in oil-filled transformers. This nondestructive test is conducted without using over voltages that could negatively impact the equipment.

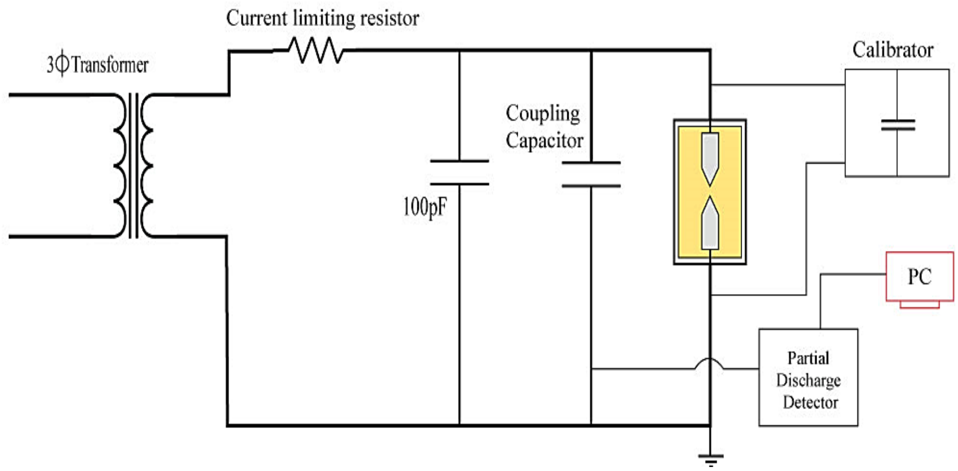


Figure 3.6: Schematic of partial discharge setup

To record the partial discharge pulse rate relative to the charge, the Partial Discharge Inception Voltage (PDIV) and pulse count are observed. The process involves applying a constant initial voltage of 5kV and then incrementally increasing the voltage in 1 kV steps, maintaining it for one minute. After reaching PDIV, the number of PD pulses per one-minute interval is recorded for each subsequent voltage step increase of 1 kV. Before conducting the PD test with high voltage, a 1pC charge pulse is fed for circuit calibration to set the test sensitivity. During this process, the partial discharge calibrator should be positioned as close as possible to the high voltage terminals to minimize errors caused by stray capacitance. Pulses below 1pC are considered as noise.

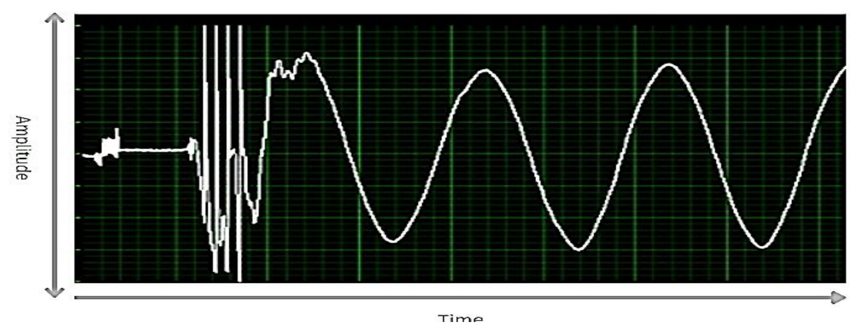
3.6 Summary

This chapter details an experimental investigation that compared the performance of transformer insulating mineral oil at low failure rates by measuring the breakdown voltage of the material under AC and impulsive voltage conditions. To determine how responsive different oil samples are to electrical shocks, tests are conducted. The impacts on AC and lightning impulse voltages are studied with various electrode designs. Numerous testing techniques, such as AC breakdown voltage, partial discharge, lightning impulse testing, FTIR spectroscopy, viscosity measurement, and flash point testing, are used to evaluate the oil's dielectric qualities. The experimental design and protocols for every test are also covered in this chapter. This opens the door to a detailed examination of the behavior of the oil.

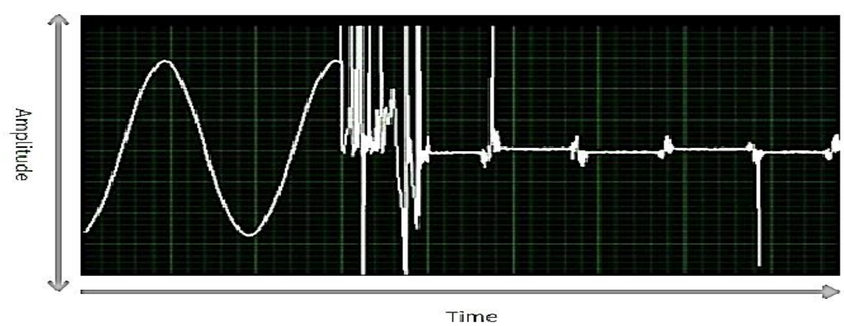
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Investigation of Breakdown Voltage AC

At a certain voltage level applied to the transformer oil, streamers formed a path that resulted in partially breakdown at some voltage value that eventually leads to complete voltage breakdown. Partial and fully breakdown voltage phenomenon can be observed in Figure 4.1, providing a clear representation of collapsing of sinusoidal ac wave.



(a)



(b)

Figure 4.1: Partially and fully breakdown in transformer oil.

The breakdown strength determination was based on the average of ten consecutive breakdown tests is shown in Figure 4.2. It's important to note that the primary objective of

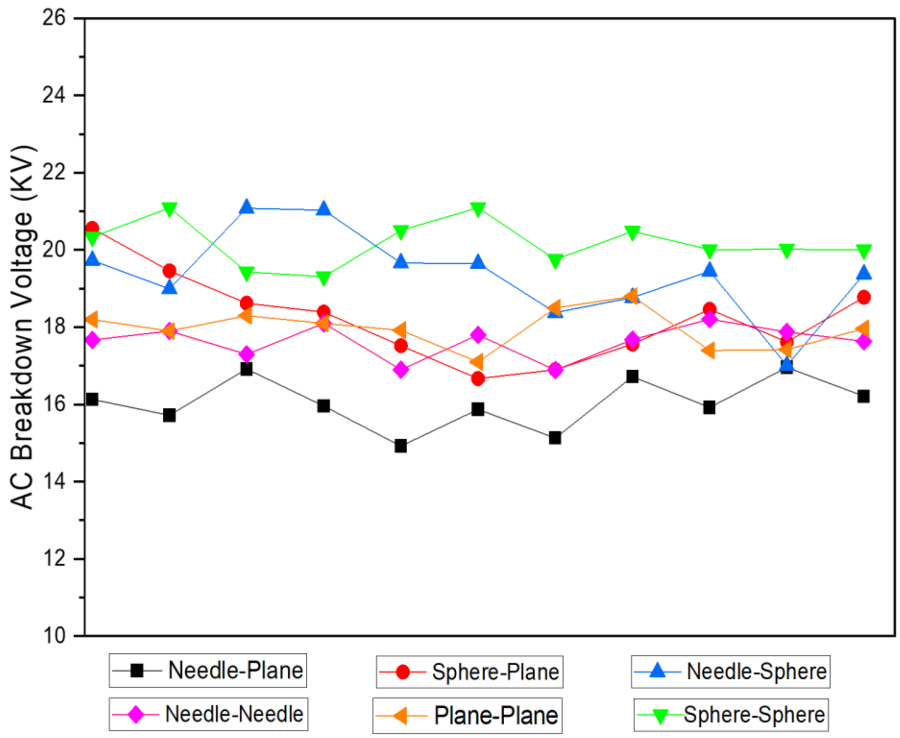


Figure 4.2: Breakdown Voltage values of virgin transformer oil at different electrode configurations.

AC breakdown voltage test is to explore the impact of varying electric fields within different electrode configurations. An average AC breakdown voltage (AC-BDV) values for transformer oil samples, maintaining a constant 1.5mm gap distance between the electrodes is given in Table 4.1. Among the various configurations studied, hemisphere electrodes emerged as possessing a uniform electric field geometry superior to all others. The curvature of the sphere electrode reduces the electric field, resulting in the highest AC breakdown voltage when compared to plane-plane and needle-plane electrodes. Quasi-uniform needle-needle and plane-plane configurations consistently demonstrated lower breakdown voltages when compared to other setups. This phenomenon can be attributed to the sharp tip of the needle electrode, which facilitates the formation of streamer paths more rapidly than other electrode types. Similarly, the plane electrode's sharp edges make it highly susceptible to streamer discharge, contributing to lower breakdown voltage values.

Table 4.1: Average AC breakdown voltage of virgin transformer oil in different electrode configuration.

Gap Size (mm)	Electrode Configuration	Average AC-BDV
1.5	Hemisphere- Hemisphere	20.56
	Hemisphere-Needle	19.03
	Hemisphere-Plane	18.49
	Plane-Plane	18.12
	Needle-Needle	17.67
	Plane-Needle	15.89

On the contrary, hemisphere-needle and hemisphere-plane configurations were characterized by non-uniform electric fields, resulting in comparatively lower breakdown voltages than uniform field and ends with sparking between electrodes. In this setup, an electrical arc possesses high energy due to the cumulative effect of electron avalanches. Eventually, this process creates a conductive bridge from the needle tip to the midpoint of the hemisphere-grounded electrode. Consequently, the temperature of the needle electrode rises gradually. As the streamers persist, an increasing number of electrons are emitted from the positive polarity needle electrode. This excessive rise in both temperature and the number of moving electrons can potentially damage the oil's properties and lead to carbonization. This observation highlights the critical role of field uniformity in breakdown strength.

In the context of high-voltage experiments, the needle-plane geometry is favored due to its ability to generate a strong electric field even at moderate voltage levels. Out of all the electrode combinations, plane-needle geometry turned to have lowest breakdown voltage value due to their sharp curvature edges and sharp needle tip. It's worth emphasizing that breakdown voltages tend to be higher in uniform fields as opposed to non-uniform setups where field intensity exhibits variations.

4.2 Investigation of Breakdown Voltage Impulse

A sample breakdown or absence are two possible outcomes of a single lighting impulse test. It was easy to determine which of the two occurred due to the sound phenomena associated with a breakdown and voltage collapse observed in the recorded voltage waveform according to the IEC 60897 standard. Figure 6 displays two contrasting scenarios in which the breakdown occurred and did not occur.

Figure 4.3: (a) Positive Lighting Impulse without breakdown (b) Positive lighting impulse with breakdown.

Figure 4.4: (a) Negative Lighting Impulse without breakdown (b) Negative lighting impulse with breakdown.

The results of the analysis of mineral oil measurements using the up-and-down procedure for all six configurations are shown in the Table below. In the column "Event," Y represents the occurrence of breakdown and N represents its absence. According to the method's guidelines, 20 rounds have been fired since the first breakdown. The main aim of this research is to compare the dielectric withstand in lightning impulse voltages to that determined in AC in prior work under the identical experimental settings and electrode configurations.

Because of the symmetry of electrode arrangement, the polarity effect will be less noticea ble in homogeneous or quasi-uniform electric fields. While it is more visible in non-uniform polarity configurations.

Table 4.2: Applied impulse voltage and occurrence of possible number of events in hemisphere-hemisphere electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
80	N	87.31	N
84	N	91.6	N
88.2	N	96.26	Y
92.61	Y	91.44	Y
87.97	N	86.86	N
92.37	Y	91.2	N
87.75	N	95.77	Y
92.137	Y	90.98	N
87.53	N	95.53	Y
91.91	Y	90.75	Y

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
80	N	96.51	Y
84	N	91.68	N
88.2	N	101.08	Y
92.61	N	96.03	Y
97.24	Y	91.22	N
92.37	N	95.99	Y
96.99	N	90.77	Y
101.84	Y	86.23	N
96.75	N	90.54	N
101.69	Y	95.07	Y

Table 4.3: Applied impulse voltage and occurrence of possible number of events in plane-plane electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
40	N	48.24	N
42	N	50.66	N
44.1	N	53.19	Y
46.30	N	50.53	Y
48.62	N	48.01	N
51.05	Y	50.41	Y
48.49	Y	47.88	N
46.07	N	50.28	Y
48.37	N	47.76	Y
50.78	Y	50.15	Y

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
40	N	39.49	N
42	N	41.47	N
44.1	N	43.54	Y
46.30	Y	41.36	Y
43.99	N	39.31	Y
46.18	N	37.33	N
48.49	Y	39.20	N
46.07	Y	41.16	N
43.96	Y	43.22	Y
41.57	Y	41.06	Y

Table 4.4: Applied impulse voltage and occurrence of possible number of events in hemisphere-needle electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
45	N	54.28	N
47.25	Y	57.01	Y
44.88	N	54.15	Y
47.13	N	51.44	Y
49.48	N	48.87	Y
51.96	Y	46.82	N
49.36	N	48.74	N
51.83	N	51.18	N
54.24	Y	53.74	Y
51.73	N	51.05	Y

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
35	N	46.66	Y
36.75	N	44.33	Y
38.58	N	42.11	Y
40.51	N	40.01	Y
42.54	N	38.01	Y
44.66	N	36.111	N
46.90	N	37.91	N
49.24	Y	39.81	Y
46.78	Y	37.82	Y
44.42	N	35.93	N

Table 4.5: Applied impulse voltage and occurrence of possible number of events in hemisphere-plane electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
65	N	58.02	N
68.25	N	60.98	N
71.66	N	64.3	N
75.66	Y	67.23	Y
71.42	Y	63.87	N
67.90	Y	67.64	N
64.51	Y	70.24	N
61.02	Y	73.75	N
58.22	Y	77.44	Y
55.31	N	73.56	N

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
80	N	71.48	N
84	N	75.95	N
88.2	Y	78.80	Y
83.79	Y	74.86	Y
79.6	Y	71.12	Y
75.62	Y	67.56	N
71.83	Y	70.94	Y
68.24	N	67.39	N
71.65	Y	70.76	N
68.08	N	74.30	Y

Table 4.6 Applied impulse voltage and occurrence of possible number of events in plane-needle electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
40	N	42.18	N
42	N	44.29	N
44.1	N	46.51	N
42.596	N	48.83	Y
44.71	Y	46.39	Y
42.52	N	44.07	Y
44.65	N	41.86	N
46.88	Y	43.96	Y
42.29	Y	41.76	Y
40.17	N	39.67	N

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
40	N	43.66	Y
42	N	41.47	N
44.1	Y	43.47	N
41.89	N	45.72	N
43.98	N	48.02	Y
46.189	Y	45.61	Y
43.87	Y	43.33	Y
41.68	N	41.16	N
43.77	Y	43.22	Y
45.95	Y	41.06	N

Table 4.7: Applied impulse voltage and occurrence of possible number of events in needle-needle electrode configuration.

Positive Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
35	N	46.66	N
36.75	N	49.01	N
38.58	N	51.45	N
40.51	Y	54.03	Y
38.49	N	51.32	Y
40.12	N	48.75	Y
42.43	N	46.31	Y
44.55	N	44.01	N
46.78	N	46.02	Y
49.125	Y	43.21	Y

Negative Lighting Impulse

Voltage (kV)	**Event**	**Voltage (kV)**	**Event**
50	N	43.66	Y
52.5	N	51.73	N
55.13	Y	54.31	N
52.36	Y	57.02	N
49.63	Y	59.88	Y
46.19	N	56.88	Y
49.54	Y	54.05	Y
47.04	N	51.34	Y
51.85	N	48.77	N
54.45	Y	51.21	Y

4.2.1 Statistical Analysis of Breakdown Voltage Under Lighting Impulse with Weibull Probability Plot

Statistical analysis was conducted to assess conformity of breakdown voltage with Weibull probability distribution. Weibull statistical analysis approach to evaluate breakdown voltage values in the context of lighting impulse voltage failure examination. It highlights the application of this method to calculate breakdown voltages, determine shape and scale parameters, and derive probability density functions (pdf) for a more thorough understanding of the data.

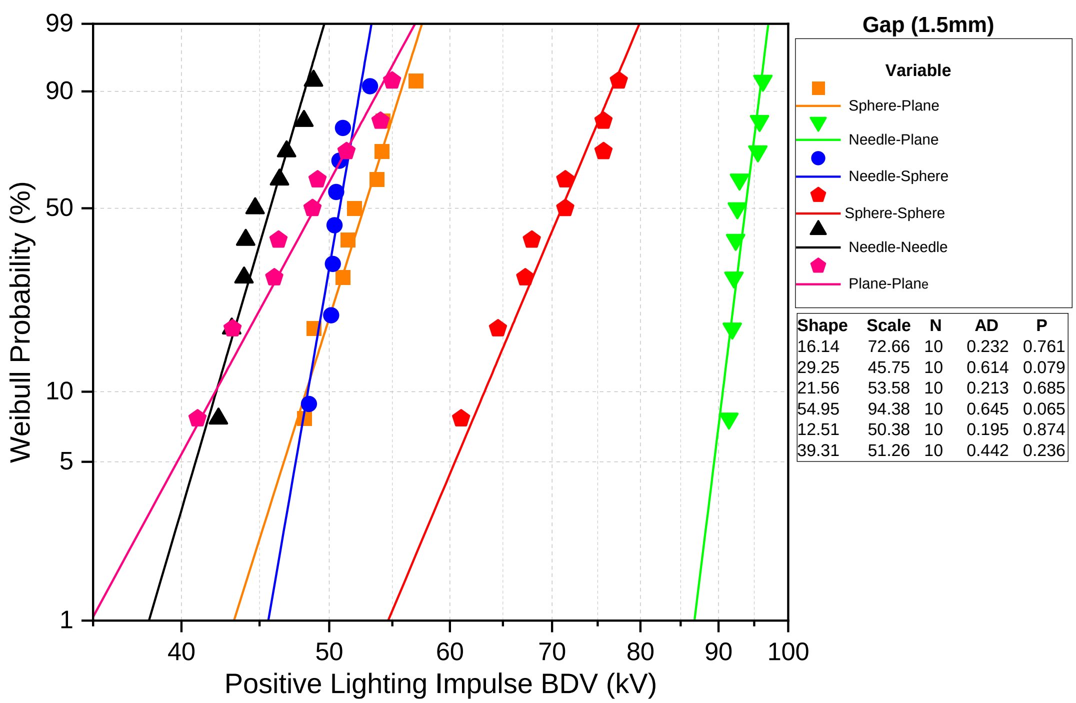


Figure 4.5: Probability Weibull distribution for positive impulse breakdown voltage.

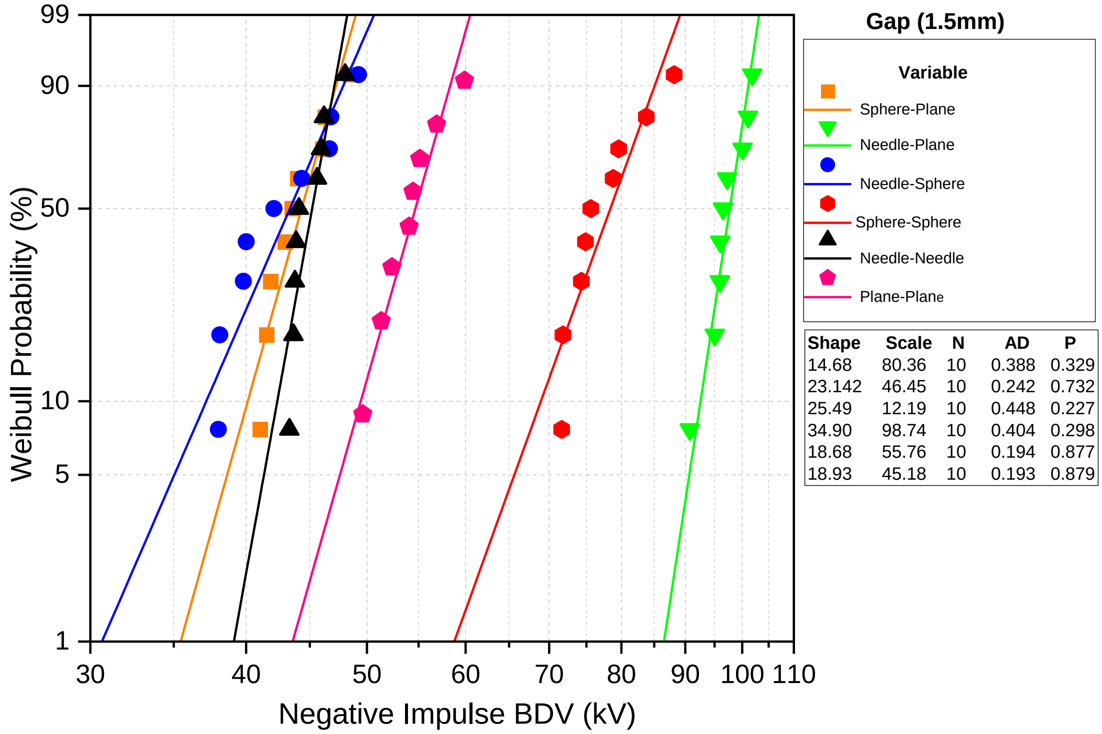


Figure 4.6: Probability Weibull distribution for negative impulse breakdown voltage.

The Weibull statistical analysis of breakdown voltage characteristics test results is conducted using the following formula.

$$F(x) = 1\text{-exp}\ [-\ (x/\ \alpha)]^{\beta}$$

α = Scale parameter,

β= Shape parameter,

x = Breakdown voltage value

In the estimation of mineral oil's withstand voltage, a rigorous statistical analysis is employed, if the breakdown voltages of the oil adhere to a specific parametric distribution. Two key parameters play a pivotal role in this estimation: the shape parameter, which signifies the degree of consistency in the oil's performance, with higher values denoting greater uniformity, and the scale parameter, which reflects the dispersion or variability of the experimental data. Moreover, the number of data points considered (N) is a crucial factor in assessing the robustness of the estimation. To validate the accuracy of the chosen parametric distribution, the Anderson-Darling (AD) test is utilized, quantifying the alignment between the fitted line and the empirical distribution function. The p-values derived from this test offer essential insights into the reliability of the data and the distribution characteristics, ultimately contributing to a comprehensive estimation of mineral oil's withstand voltage.

4.3 Partial Discharge Measurement

Assessing the partial discharge (PD) characteristics of transformer insulating oils is crucial, as prolonged PD exposure can lead to sludge formation. Partial discharges indicate the presence of gaseous cavities within dielectric liquids. According to the IEC 60270 standard (High-voltage test techniques - Partial discharge measurements), PDIV stands for "Partial Discharge Inception Voltage." It is defined as the applied voltage at which "repetitive partial discharges are first observed in the test object." This is a critical parameter for evaluating the insulation's integrity and quality as the voltage is gradually increased from a lower value where no partial discharges are observed. When the test voltage exceeds the PDIV and then falls to a certain level, the partial discharge process ends at the extinction voltage (PDEV). The PDIV value indicates how electrical insulation reacts to partial discharges. Furthermore, the partial.

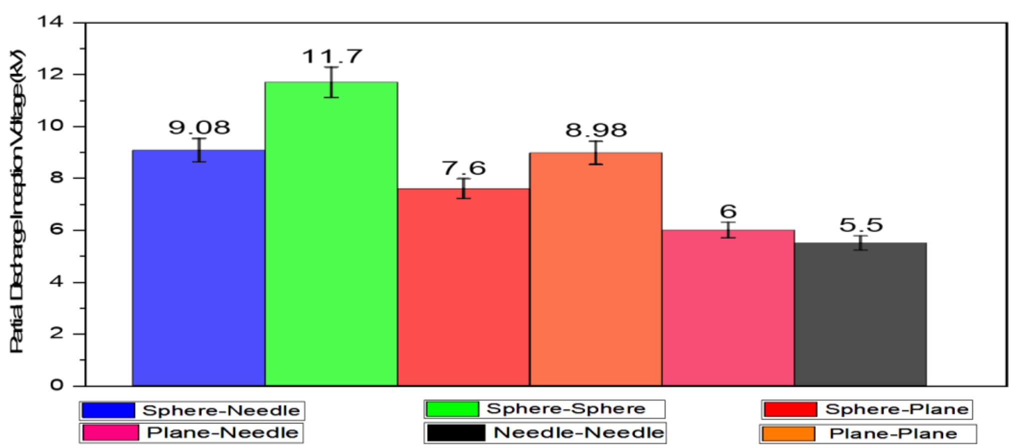
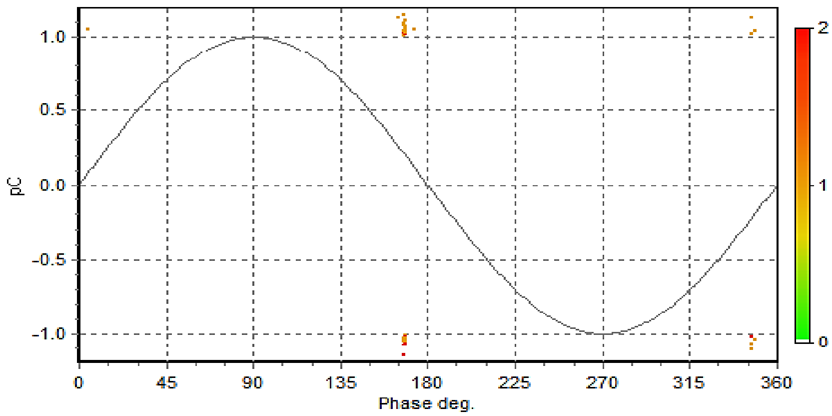


Figure 4.7: Partial Discharge Inception Voltage (PDIV) for six electrode configurations.

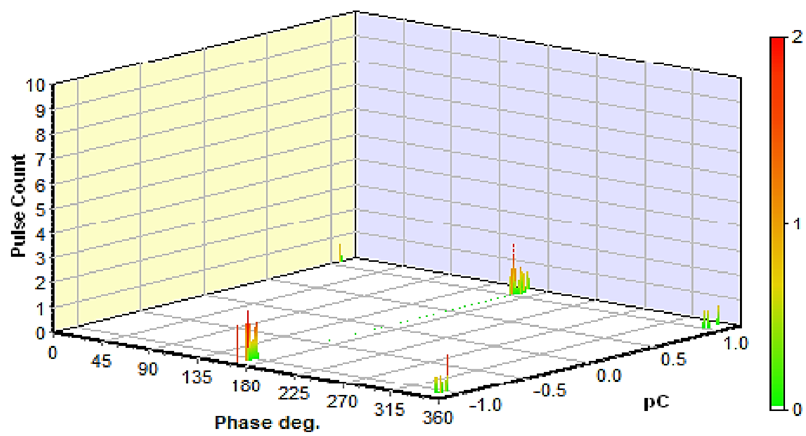
discharge is quantified by the detected electric charge (Q), which is directly proportional to the intensity of PD and can be used to compare different conditions. It should be noted that, despite the severe breakdown, PD activity does not typically lead to harmful breakdown conditions, even at elevated test voltages, as the PD intensity remains relatively low.

To examine the size and frequency of PD events above the PDIV (Partial Discharge Inception Voltage), the test voltage was gradually raised beyond the PDIV up to 18 kV. At each voltage level, PD signals were recorded, filtering out any noise. Phase-Resolved PD (PRPD) patterns were also analyzed to gain insights into the characteristics of these PD occurrences. This approach helps in understanding the behavior of partial discharges once they have initiated for all six configurations (mentioned above) obtained. This experiment underlines the critical role of electrode configuration and phase angle in shaping the dynamics of partial discharge behavior.

In the sphere-sphere configuration, a visible pattern emerged. In the initial half positive cycle of the sinusoidal wave, spanning up to 90° of the phases, merely one PD event exceeding 1 PC (partial charge) was detected. However, as the voltage descended within the phase change window between 90° and 180°, a noteworthy increase in both positive and negative PD events was observed. There were no PD events between 180° and 270°. Nevertheless, a resurgence of PD activity became evident in the latter half of the cycle, spanning up to 360°, once again exceeding both 1PC and -1PC. To comprehensively visualize the intensity and distribution of these PD events within the oil, a three-dimensional (3D) graph was employed.



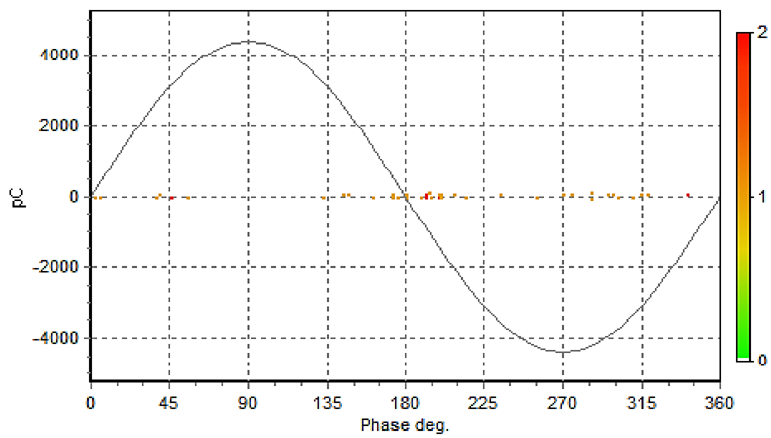
(a)



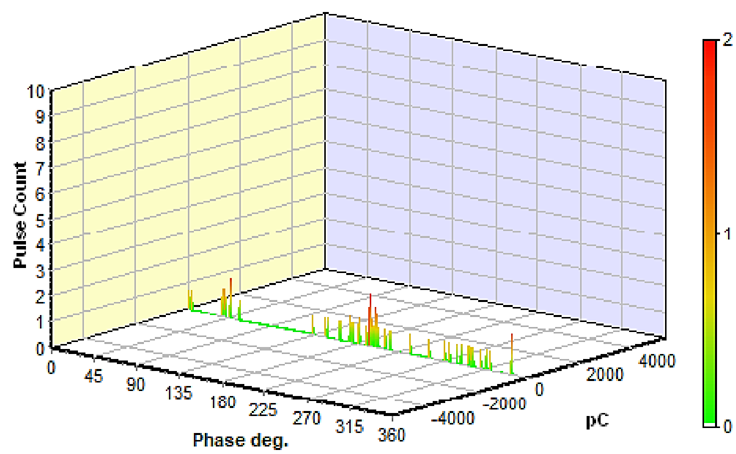
(b)

Figure 4.8: PRPD pattern of virgin oil at hemisphere-hemisphere configuration (a) 2D graph (b) 3D graph

In comparing the plane and hemisphere electrode configurations, a notable discrepancy emerged, revealing the plane electrode's sharper edges. The positive terminal of the PD connected to the plane electrode, while the hemisphere electrode remained grounded. This setup facilitated the observation of a distinct PD pulse pattern during the positive half cycle, characterized by a smaller charge transfer than the following negative pulse, all initiated above the PD inception voltage (PDIV) set at 7.6 kV_{rms}. Initially, within the first positive peak of the wave cycle, a relatively modest number of PD pulses were detected. However, as the voltage progressively decreased, the pulse count exhibited a steady rise, accompanied by a visible increase in the intensity of the charge, measured in picocoulombs (pC). This observation highlighted the complex nature of PD behavior within the context of these distinctive electrode configurations.



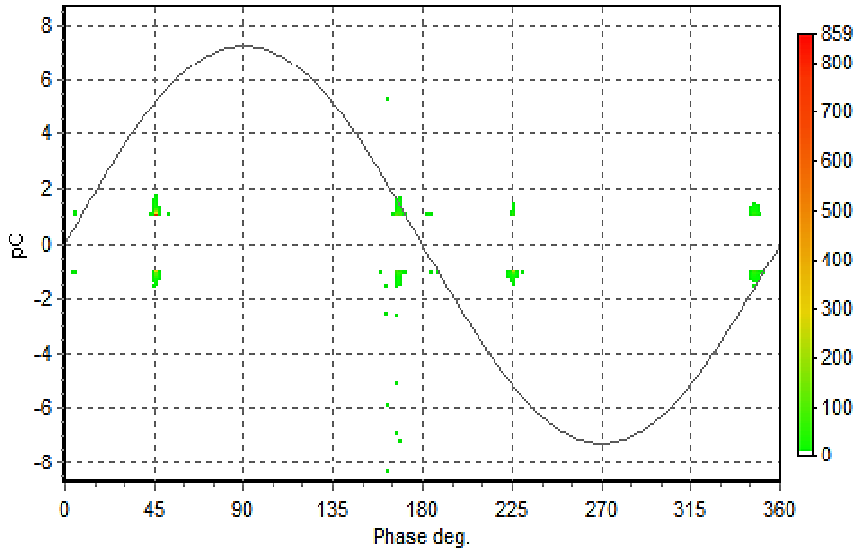
(a)



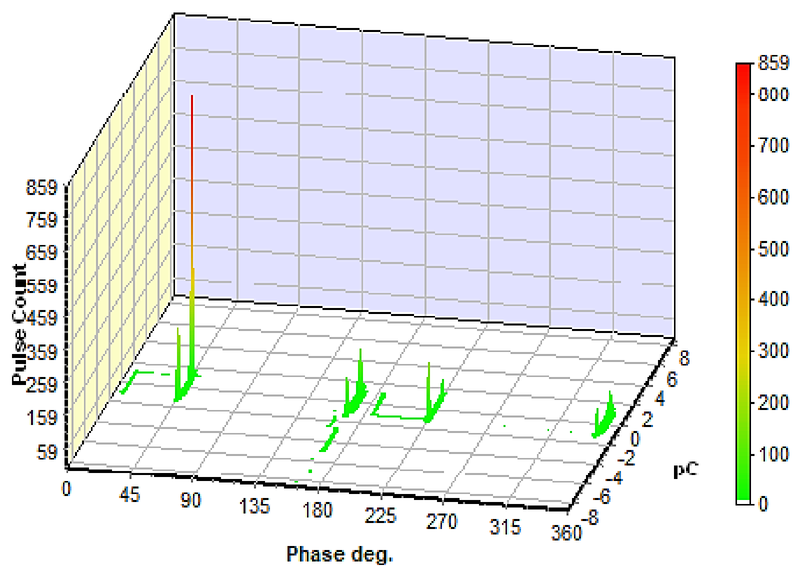
(b)

Figure 4.9: PRPD pattern of virgin oil at hemisphere-plane configuration. (a) 2D graph (b) 3D graph

In the experimental setup, the needle electrode was positively charged, while the hemisphere electrode was grounded. Notably, at the start of the positive quarter cycle at 45°, distinct patterns of partial discharge exceeding 1 picocoulomb (pC) commenced along the needle electrode. This phenomenon continued consistently throughout the entire cycle, particularly at 180°, 225°, and near the 360° mark. The strongest intensity of partial discharge was observed at 45°, as visually confirmed through a three-dimensional (3D) graph representation.



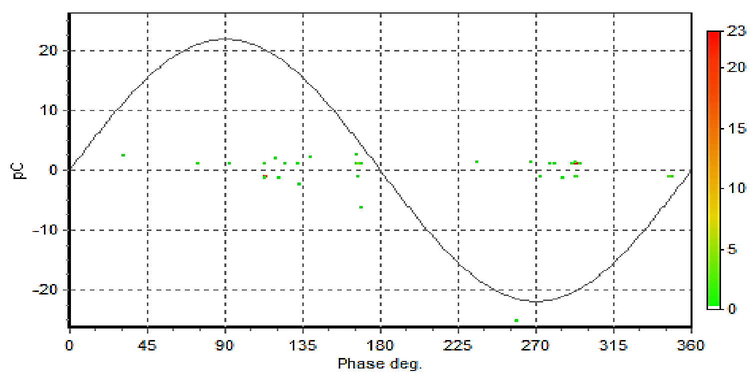
(a)



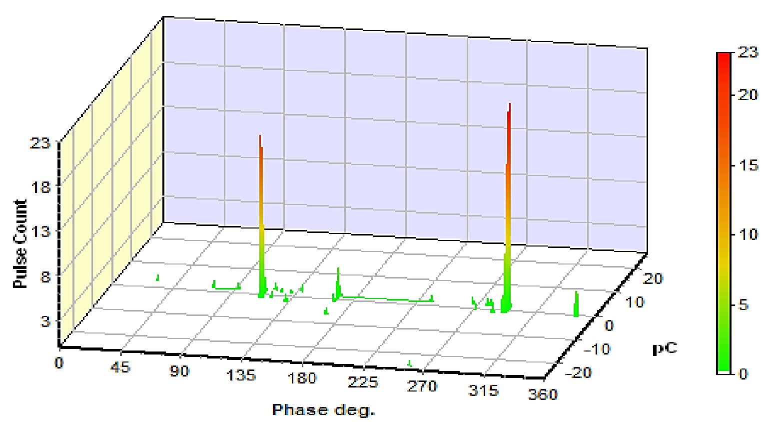
(b)

Figure 4.10: PRPD pattern of virgin oil at hemisphere-Needle configuration. (a) 2D graph (b) 3D graph

In the needle-needle electrode configuration, a distinct and uniform pattern of discrete partial discharge events was observed. Interestingly, the same number of pulses and stress levels were detected at both electrodes. The electric field around the needle electrode may not be sufficiently strong to maintain the ionization of liquid molecules at relatively low voltage levels, leading to the disappearance of partial discharge (PD). This symmetry in partial discharge behavior can be attributed to the identical shape and size of the electrodes in use. Consequently, nearly equivalent partial discharge intensities were observed at both electrodes, reaffirming the influence of electrode characteristics on the observed phenomena in this experiment.



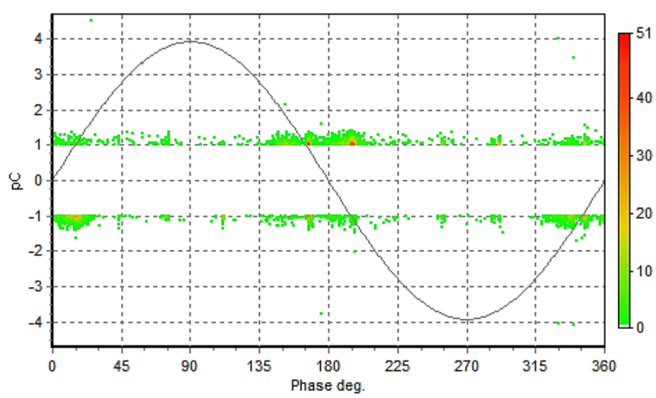
(a)



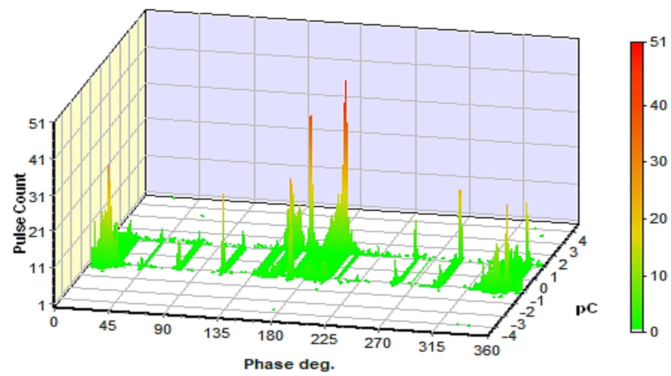
(b)

Figure 4.11: PRPD pattern of virgin oil at Needle-Needle configuration. (a) 2D graph (b) 3D graph

In the plane-needle configuration, the plane electrode was linked to the positive polarity, while the needle electrode was grounded. A significant count of positive and negative partial discharge pulses was detected, consistently exceeding the 1 picocoulomb (pC) threshold. The highest intensity of these discharges was observed within the phase range of 135° to 225° of the wave cycles. In power equipment, the needle-plane geometry can exist in the form of unavoidable sharp edges or may be represented by conducting particles. These particles can be either stuck at a barrier or freely moving within the bulk oil. The "inception voltage" refers to the voltage level at which the first few partial discharges (PDs) occur within a span of one minute. It signifies the voltage point at which the initial PD activity is observed in the system. A notable observation emerged: the plane electrode's sharp edges appeared to induce a greater number of partial discharge events compared to the needle electrode. This observation specified the influence of electrode geometry, particularly sharp edges, as a contributing factor in the generation of partial discharge pattern.



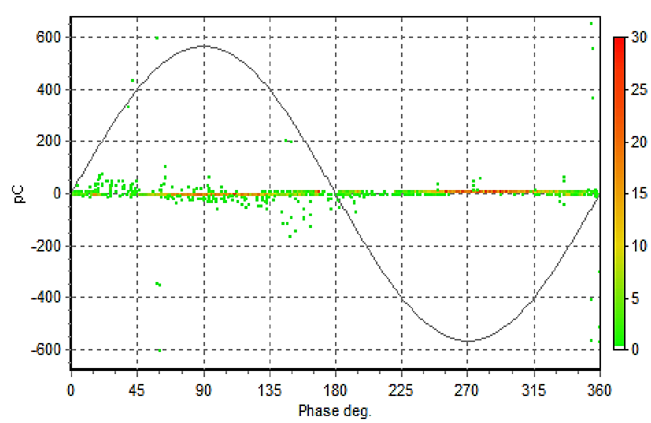
(a)



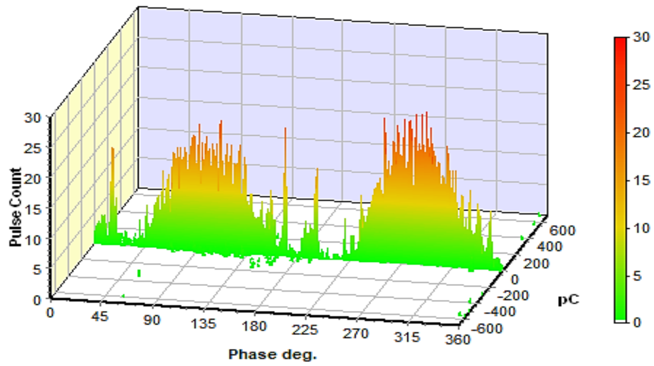
(b)

Figure 4.12: PRPD pattern of virgin oil at Plane-Needle configuration. (a) 2D graph (b) 3D graph

In the setup employing plane-plane electrodes, a noteworthy consistency was observed in terms of equal potential during both the positive and negative cycles of the wave. During the initial half cycle, distinct and discrete values of partial discharge was detected. A three-dimensional (3D) graph representation of the partial discharge pattern revealed a consistent occurrence along both electrodes, with identical intensities observed on both sides. This symmetrical behavior reaffirms the equilibrium in partial discharge activity between the two plane electrodes, further underlining the importance of electrode configuration in influencing experimental outcomes.



(a)

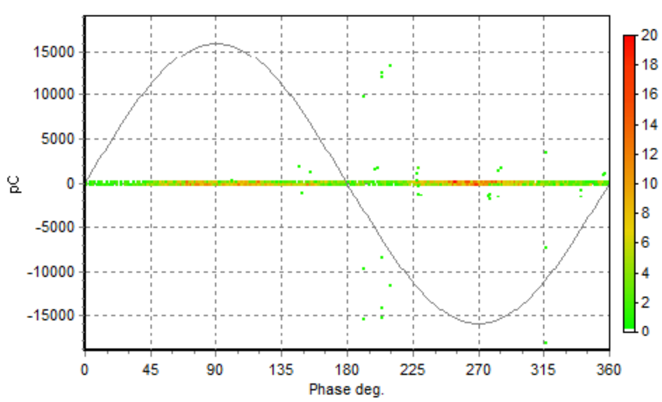


(b)

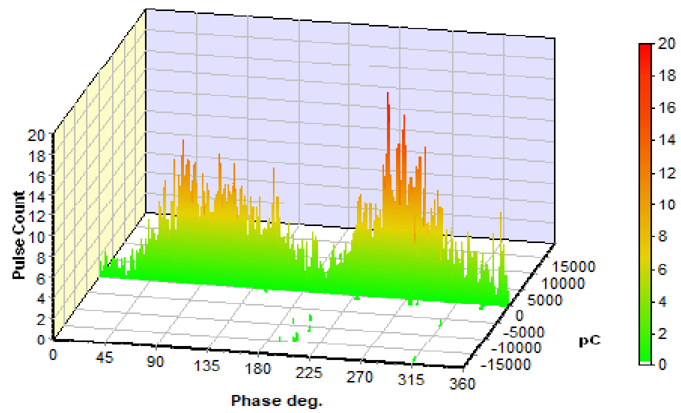
Figure 4.13: PRPD pattern of virgin oil at Plane-Plane configuration. (a) 2D graph (b) 3D graph

4.4 Partial Discharge in Electrically Tested Oil

When compared to virgin (unused) oil, the tested oil demonstrated a higher frequency of partial discharge in the sphere-sphere electrode configuration. This variation can be attributed to the moisture level and contaminants in the tested oil, which are exacerbated by the electric stress applied during testing. The tested oil had a significantly higher charge value than the virgin oil, indicating that environmental circumstances and electrical strain influence the oil's partial discharge behavior.



(a)



(b)

Figure 4.14: PRPD pattern of electrically tested oil at hemisphere-hemisphere configuration. (a) 2D graph (b) 3D graph

4.5 Chemical Changes Analysis

Comparing FTIR patterns of virgin and electrically tested oil reveals significant differences, highlighting the oil's sensitivity to even minor electrical activity, essential for maintaining electrical equipment. There is a notable distinction in the FTIR spectra between the virgin and electrically tested oil samples. This observation confirms that even minimal electrical discharge has an impact on the chemical structure of transformer oil.

Table 4.8: Functional group and absorbance change between virgin and electrically tested oil.

Wave number (cm^{-1})	**Functional group**	**Intensity (Virgin oil)**	**Absorbance (Virgin oil)**	**Absorbance (Tested oil)**	**Loss Percentage**
2921.01	Alkane & Stretching (C–H)	Strong	0.3196	0.2814	11.9524
2852.72	Alkane & Stretching (C–H)	Medium	0.2308	0.2016	12.6516
1458.23	Methylene & Bending (C-H)	Strong-Medium	0.1138	0.1486	30.5801
1378.07	Alcohol & Bending (O-H)	Medium-weak	0.0604	0.0751	24.3377
722.12	Methylene & vibrational (C-C)	Weak	0.0343	0.0280	18.3673

During the electrical aging process, alterations are likely to have occurred in a carbon group component, which can impact the performance of the transformer oil. Low-energy corona discharges can result in the generation of methane and hydrogen, along with smaller quantities of ethylene and ethane. Additionally, significant amounts of hydrogen or acetylene, or smaller amounts of ethylene, may be produced because of arcing. Overheating oil might produce ethylene and methane.

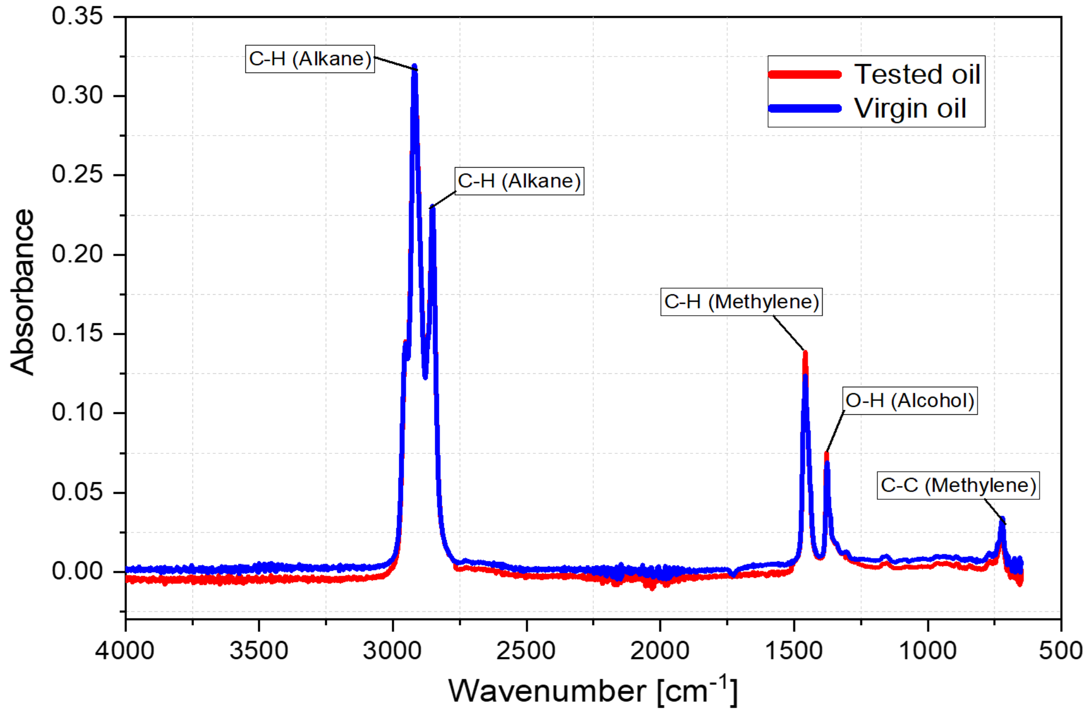


Figure 4.15: FTIR absorbance spectra in the range of 4000 cm-1- 600 cm-1 of mineral virgin and electrically tested oil sample.

Analysis of an absorption spectrum reveals three main regions with distinct functional groups. The first region exhibits strong intensity and bending vibrations. The second region, between 1300 cm−1 and 1550 cm−1, displays absorption peaks, notably at around 1376 cm^{-1} and 1460cm^{-1}.

Low levels of electrical discharge energy can cause the disruption or fracture of carbon-hydrogen (C-H) and carbon-carbon (C-C) bonds. The decrease in absorption intensity in CH_2 and CH_3 in the tested oil is attributed to the gradual deterioration of bonds in the mineral insulating oil, electrical discharge energy is the primary cause of this phenomenon, resulting in the production of fault gases. The absorption of these gases is particularly sensitive to minor alterations in molecular structure and is often referred to as the "fingerprint" region due to its unique characteristics.

The peak at first region 2921.01 cm^{-1} is associated with the (C-H) stretching of saturated carbon-carbon bonds and ascribed to $-CH_2$ vibrations is a small peak at 2852.72 cm^{-1}, associated to $-CH_3$ vibrations.

The peaks in the second region between 1300 and 1500 cm−1, at peak positions 1458.23 and 1378.07 cm−1, are attributed to (C-H) bounding vibrations. These vibrations produce a similar pattern to the primary $-CH_2$ and $-CH_3$ vibrations, which peak at 2921.01 and 2852.72 cm−1, respectively. The absorption spectra (630-800 cm−1) exhibit a peak at 722.12 cm−1, indicating the presence of alkenes with carbon-carbon bonds that have been stretched (C–H) out of plane. Due to degradation, electrically tested oil has a lower absorbance than fresh oil because C-H bonds are weak and can break under low-energy faults, producing fault gasses such ethylene, acetylene, hydrogen (H_2), and methane (CH_4).

The percentage difference between the tested sample and the virgin sample is between 11% and 12%. According to Table 2, the tested sample's percentage gain was between 24% and 30%, and it subsequently fell by 18%. The intensities of the absorbance peaks at 722.12 cm−1, 2852.72 cm−1, and 2921.01 cm−1 are observed to decrease. The decrease in the absorption intensity of CH_2 (722.12, 2852.72, 2921.01) cm−1 and CH_3 2952.72 cm−1 in the old oil samples is due to the broken C–C and C–H bonds in the mineral oil. Electrical discharge energy is the driving force behind the gradual degradation process that led to this event.

However, using FTIR spectroscopy, three samples—plane-plane, plane-needle, and needle-plane—are examined to see how the samples' chemical composition changes when exposed to AC breakdown voltage. The sensitivity of oil to electrode morphologies and breakdown voltage activity is highlighted by comparing the FTIR peaks of damaged oil that was electrically tested using three different electrode configurations. This comparison is crucial for the maintenance of transformer equipment. The FTIR spectra of oil samples that were electrically tested for three different configurations differ significantly from one another.

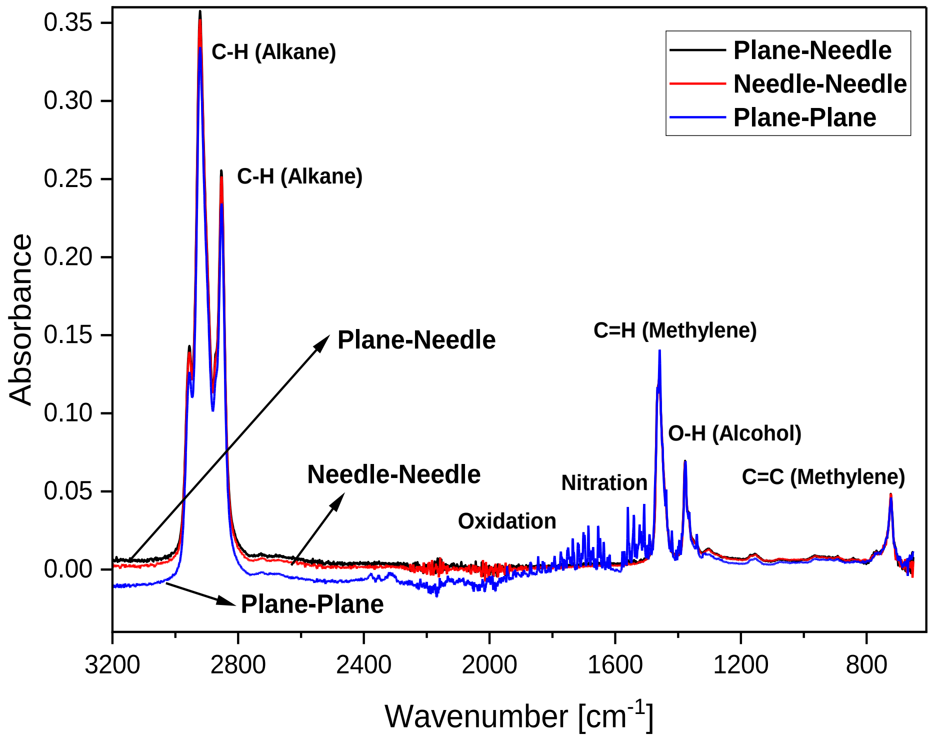


Figure 4.16: FTIR spectra of transformer mineral oil tested samples under various electrode configurations.

The difference between the three spectra can be easily seen in the large area of the C-H functional group peaks which is due to severe oxidation and degradation in the plane-plane (P-P) configuration sample in the Table 4.9. While almost similar functional group peaks and absorbance level noticed for plane-needle (P-N) and needle-needle (N-N) configuration.

Table 4.10: FTIR spectra peaks absorbance values for three samples.

Wavelength (cm^{-1})	**Absorbance (P-N)**	**Absorbance (N-N)**	**Absorbance (P-P)**
2921	0.358	0.341	0.313
1459	0.124	0.125	0.147
1375	0.061	0.063	0.065

Wavelength (cm^{-1})	Absorbance (P-N)	Absorbance (N-N)	Absorbance (P-P)
723	0.048	0.049	0.044

In the first peak at 2921 cm^{-1}, it is noticed that plane – needle and needle-needle configuration tested samples showed the highest peak against absorbance level at 0.358 and 0.341 while, plane-plane configuration tested sample showed lowest C-H functional peak at 0.313. On the other hand, great number of oxidation and nitration peaks observed in plan-plane configuration sample between 1700-1500 cm^{-1}. Large amounts of hydrogen or acetylene or minor quantities of ethylene can be produced because of arcing. Overheating oil will produce ethylene and methylene.

During the electrical breakdown, changes must have occurred in a carbon group component affecting the performance of the transformer oil. Hence at 1459 cm^{-1} and 1375 cm^{-1} a significant decrease noticed in the peak of needle-needle and plane-needle configuration sample, while plane-plane configuration tested sample showed highest peak of methylene and alcoholic group at this wavelength range. Similarly, at 723 needle-needle configuration tested sample showed the highest C=C methylene functional group at 0.049 absorbance level.

4.6 Kinematic Viscosity

The results of the viscosity test show that at different shear rates and temperatures (20°C, 40°C, and 90°C), virgin oil and electrically tested transformer oil have different viscosities. The main contaminant is water moisture, but there are additional impurities that can also cause the dielectric strength of mineral insulating transformer oils to deteriorate, including conductive particles, dirt, trash, particles, and oxidation byproducts. Virgin oil had a higher viscosity at 20°C than transformer oil that had undergone electrical testing.

The viscosity of the electrically tested oil sample revealed a noticeable decrease. The precipitated paraffin may have aggregated into shorter chains along the direction of the electric field, resulting in the viscosity drop. Furthermore, when the external electric field strength increased, the diffusion coefficient decreased, which is directly related to the

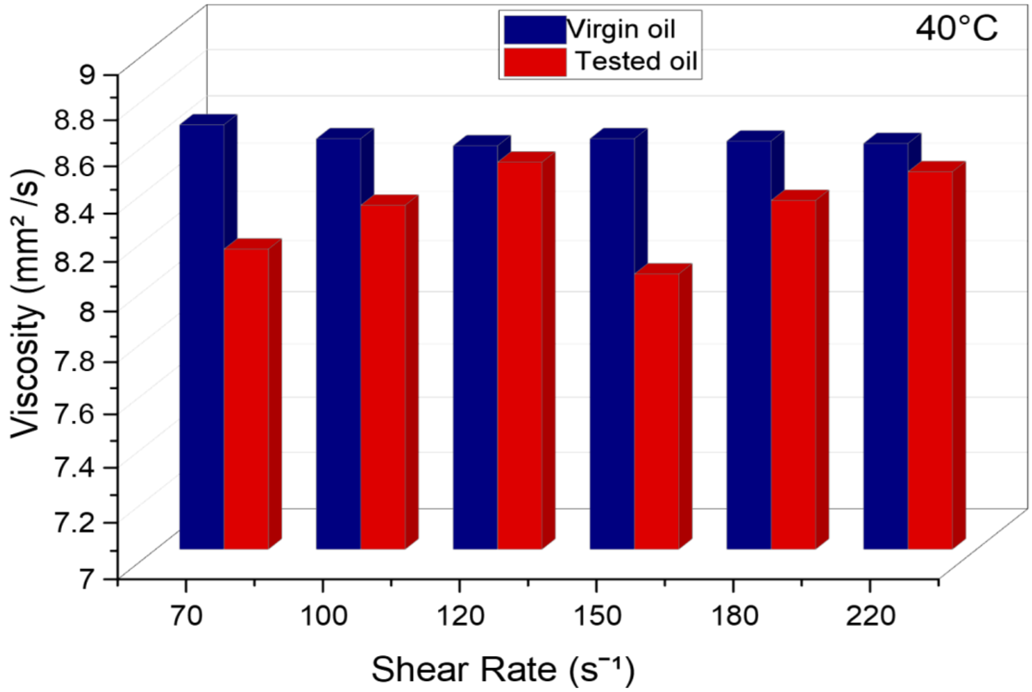


Figure 4.16: The viscosity test results in a plot of virgin and tested oil at 40°C.

observed viscosity fluctuations. Furthermore, oil viscosity followed a similar pattern to the diffusion coefficient, which measures how rapidly a liquid is distorted. When the shear rate was raised, a similar pattern was observed at temperatures of 40°C and 90°C, while the shear rate change remained constant from 70 s-1 to 220 s-1

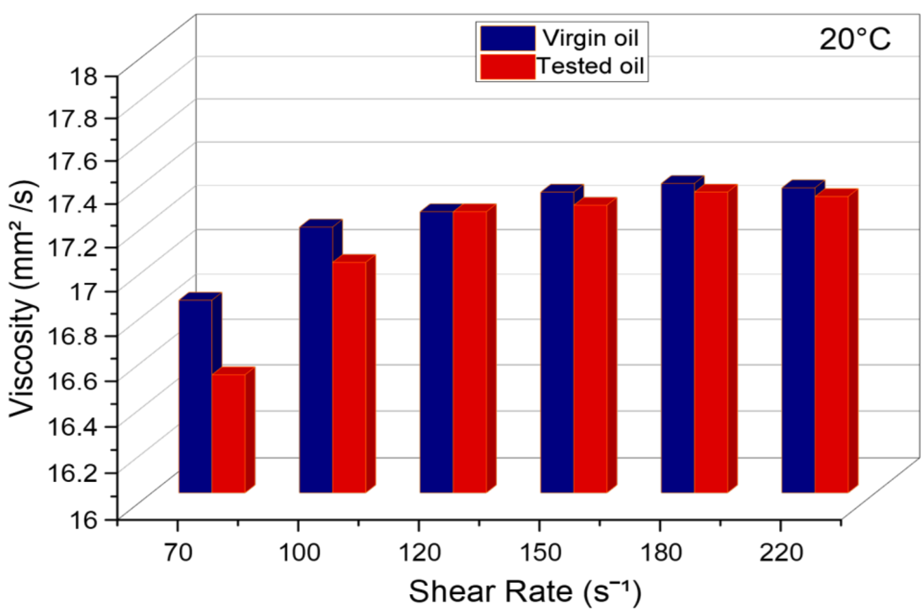


Figure 4.17: The viscosity test results plot of virgin and tested oil at 20°C.

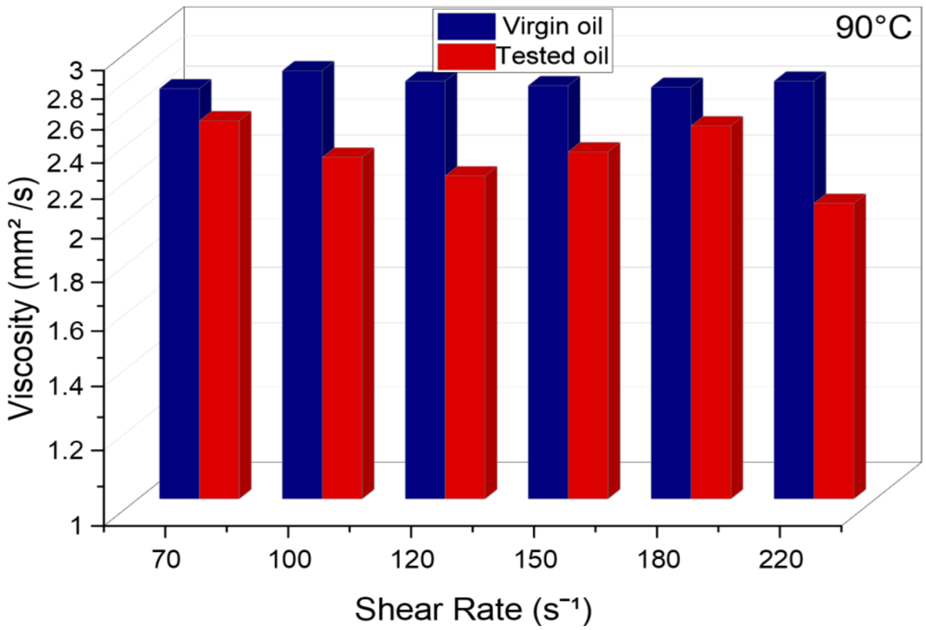


Figure 4.18: The viscosity test results plot of virgin and tested oil at 90°C.

4.7 Viscosity Trend against Temperature

Viscosity depends strongly on temperature seen in Figure 4.19. As temperature increased from 20°C to 40°C and then to 90°C, a large decline is seen in the viscosity values from 17.5 mm^2/s to 8.8 mm^2/s and then to 2.8 mm^2/s with decrease in the temperature respectively. Liquid viscosity decreases significantly as temperature rises. This reduction occurs because the attractive binding energy between molecules is weakened, leading to a

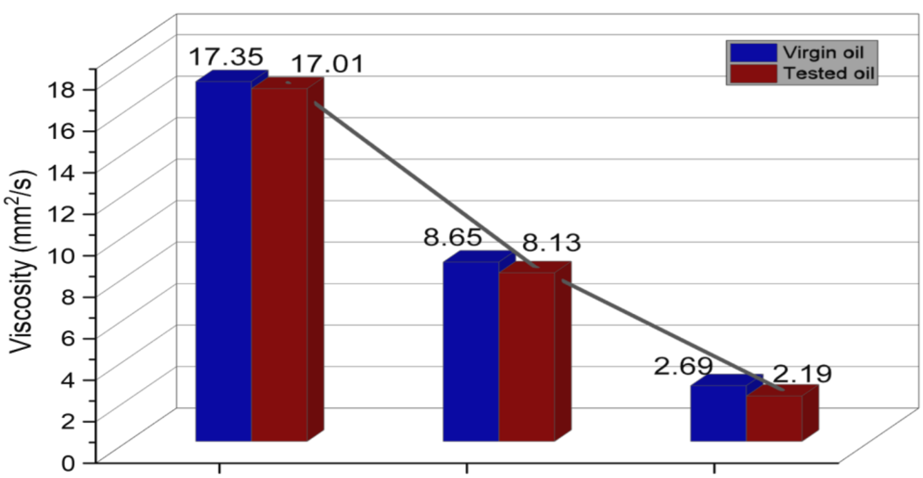


Figure 4.19: Effect of temperature at viscosity

decrease in viscosity. When the temperature of a liquid increases, it diminishes the cohesive forces between molecules while promoting a higher rate of molecular movement and interchange within the liquid.

4.8 Flash Point

The flash point of electrically tested transformer oil is observed lower than that of pure virgin transformer oil. Figure 9 illustrates this difference in flash points. The lower flash point in the electrically tested oil can be attributed to the introduction of impurities, such as carbonization, during high-voltage electrical testing. This decrease in flash point indicates a higher susceptibility to ignition when exposed to open flames or sparks. Therefore, it's essential to consider the flash point as a safety and performance parameter, especially after electrical testing, where impurities can alter the oil's properties.

It's important to note that the flash point is the temperature at which a substance emits flammable vapors that can ignite when exposed to an open flame or spark. A higher flash point, such as the 140°C value for the virgin oil, indicates that the oil is less prone to ignite when mixed with air compared to the tested oil sample with a lower flash point of 90°C. In practical terms, a higher flash point is desirable for safety reasons as it reduces the risk of accidental ignition or combustion.

Table 4.11: Flash point Test results

	Virgin oil	**Tested Oil**
Flash Point(°C)	140	90

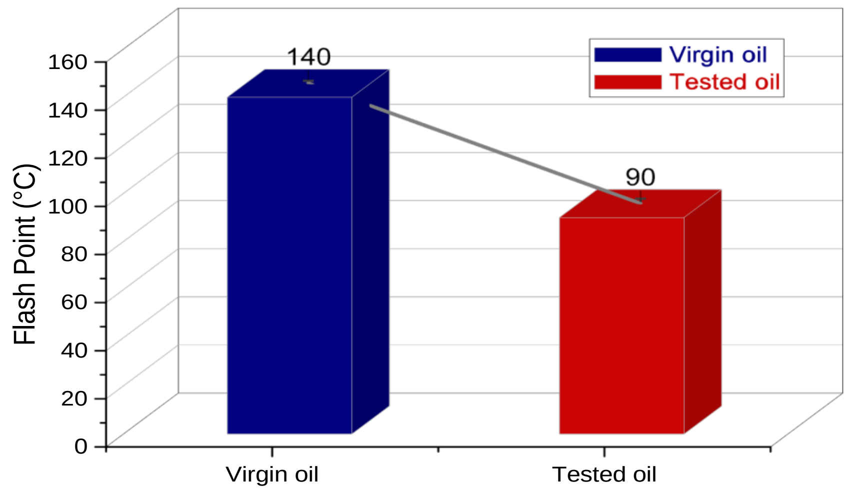


Figure 4.20: Flash point results of virgin and tested oil.

4.9 Statistical Analysis of AC Breakdown Voltage with Weibull Probability

Statistical analysis was conducted to assess conformity of breakdown voltage with Weibull probability distribution. Weibull statistical analysis approach to evaluate breakdown voltage values in the context of AC failure examination. It highlights the application of this method to calculate breakdown voltages, determine shape and scale parameters, and derive probability density functions (pdf) for a more thorough understanding of the data.

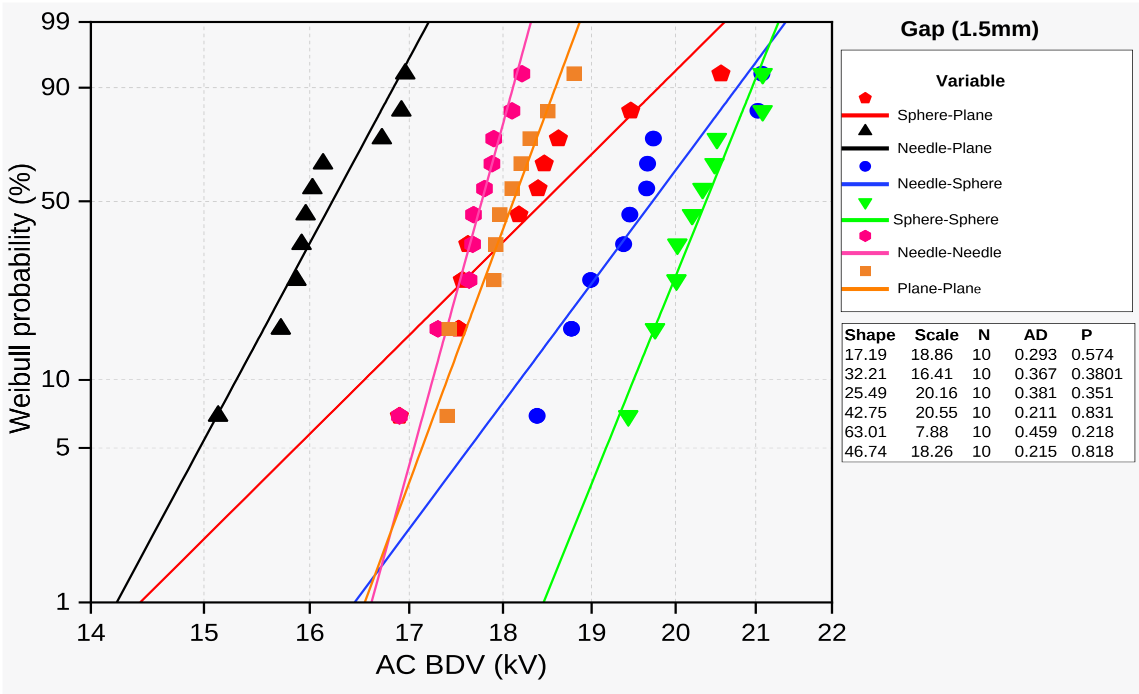


Figure 4.21: Probability Weibull distribution for AC breakdown voltage.

The Weibull statistical analysis of breakdown voltage characteristics test results is conducted using the following formula.

$$F(x) = 1\text{-exp}\,[-\,(x/\,\alpha)]^{\beta}$$

α = Scale parameter,

β= Shape parameter,

x = Breakdown voltage value

When the breakdown voltages of the insulated oil follow a given parametric distribution, the withstand voltage of mineral oil is estimated using a thorough statistical analysis. The shape parameter, which indicates the level of consistency in the oil's performance and has a higher value for better uniformity, and the scale parameter, which shows the dispersion or variability of the experimental data, are the two key factors that are important in this calculation. Furthermore, a key factor in assessing the estimation's dependability is the number of data points (N) that were reviewed. The Anderson-Darling (AD) test, which measures the degree of alignment between the fitted line and the empirical distribution function, is used to verify the accuracy of the selected parametric distribution. The p-values derived from this test offer essential insights into the reliability of the data and the distribution characteristics, ultimately contributing to a comprehensive estimation of mineral oil's withstand voltage.

Summary

This research investigates the influence of electrode configurations on the breakdown voltage of insulating mineral oil under various test conditions, emphasizing the role of electrode geometry in electrical insulation performance. The study explores multiple electrode setups—hemisphere-hemisphere, plane-plane, needle-needle, needle-sphere, plane-sphere, and needle-plane—assessing their impact on AC breakdown voltage (AC-BDV), lightning impulse breakdown voltage (LI-BDV), and partial discharge characteristics.

Key findings include:

- **Electrode Geometry Effect:** The hemisphere-hemisphere configuration exhibited the highest breakdown voltage performance for both AC and lightning impulse tests, significantly outperforming other configurations. In contrast, configurations with non-uniform fields like needle-plane showed markedly lower breakdown voltages.
- **Impact of Non-Uniform Fields**: Configurations such as needle-plane generated non-uniform electric fields, which resulted in a decreased dielectric strength of the oil. The curvature of the hemisphere electrodes helped in reducing electric field intensity, thus increasing the breakdown voltage.
- **Partial Discharge Analysis:** Examination of partial discharge pulses revealed that uniformity in electrode curvature (as seen in sphere configurations) minimizes partial discharges, while sharp edges in configurations like plane and needle contribute to increased discharge activities.
- **Chemical and Physical Changes in Oil:** The electrical stress on the oil not only reduced its flash point by 35.714% compared to virgin oil but also slightly decreased its viscosity, indicating degradation and the introduction of impurities.
- **Statistical Analysis:** Using the Weibull probability distribution to analyze breakdown events, the research provided predictions on the withstand voltage for various setups, confirmed by additional withstand tests.

In conclusion, the study underscores the critical role of electrode configuration in maintaining the integrity and reliability of insulating oil within transformers. It highlights how geometric variations can significantly affect the electrical breakdown characteristics and overall performance of the oil, providing essential insights for optimizing electrical insulation in high-voltage equipment.

CHAPTER 05: CONCLUSION AND FUTURE WORK

5.1 Research Areas

This MS thesis presents an extensive study on the breakdown mechanism in transformer liquids under AC and lightning impulse voltages, considering various electrode field configurations. Partial discharge tests were conducted for all field configurations. To analyze the effects of high voltage stress on the oil, FTIR spectroscopy, viscosity, and flash point tests were performed. Through experimental research, the thesis achieved its objectives and yielded valuable findings. The main research areas covered in this thesis include:

Breakdown mechanism in uniform fields under AC and lightning impulse voltages

- Measurement of the dielectric strengths of transformer liquid
- Studies on the effect of electrode configurations on the breakdown strengths of mineral oil
- Partial discharge experiments and analysis of results for all field configurations using PRPD graphs for AC only
- Probability Weibull statistical analysis

Measurement of partial discharge phenomena

- Implementation of test procedures for PDIV measurement in mineral oil
- Experimentation on PD features at AC voltage in mineral oil

Breakdown mechanism in divergent fields under AC and lightning impulse voltages

- Investigation of breakdown behaviors in non-uniform fields
- Using various electrode designs to determine the fault gasses in oil during partial discharge faults.

Oil quality deterioration check for electrically breakdown tested oil

- Viscosity and flash point tests

Summary of Main Findings and Results

In conclusion, this thesis has evaluated multiple electrode setups concerning their performance under AC voltage, partial discharge, and lightning impulse tests. The results have revealed significant variations in breakdown voltages and behaviors for different configurations.

First, because a continuous bridge was formed between the electrodes in the needle-plane structure, the AC breakdown voltage (AC-BDV) was noticeably lower. In contrast to plane-plane and hemisphere-plane electrodes, the needle-plane configuration produced an uneven electric field, which reduced the dielectric strength. On the other hand, the hemisphere electrode's curvature reduced the electric field and increased the breakdown voltage. Moreover, the magnitude of partial discharge pulses demonstrated the influence of electrode geometry, wherein uniformity was impacted by spherical curvature, sharp needle tips, and sharp edges in plane electrodes.

The findings can be categorized as follows:

Uniform Configuration: The hemisphere-hemisphere setup demonstrated superior performance, with higher AC-BDV and standard lightning impulse breakdown voltage compared to other configurations.

Quasi-uniform Configurations: Plane-plane and needle-needle setups displayed relatively lower AC-BDV values compared to the hemisphere-hemisphere configuration.

Non-Uniform Configurations: The needle-sphere, plane-sphere, and needle-plane setups exhibited even lower AC-BDV values, making them less favorable configurations. On the other hand, higher partial discharge activity and PDIV value was observed in plane-plane configuration as compared to the other two configurations.

Limitation

There is a limitation to this research that oil tends to regain its properties over time. Therefore, it is essential to conduct FTIR analysis immediately after the breakdown tests on the samples. In future, mineral oil properties can be studied after exposure to impulse voltage breakdown to the oil by using the same configurations as used in this research.

Electrical breakdown stresses can result in carbonization in oil, attributed to the breakage of CH bonds, as indicated by FTIR analysis. The FTIR analysis indicated a significant accumulation of oxidation and nitration in the plane-plane configuration sample, whereas similar peaks for functional groups were observed in the other two configurations.

In summary, this research underscores the significance of electrode configuration in preserving the reliability of insulating oil in transformers and quantifies the impact of AC voltage setup on breakdown voltages. Through partial discharge and FTIR test, this research observed that electrical breakdown in the oil due to the plane-plane configuration leads to the introduction of impurities and initiates chemical changes, resulting in a severe reduction in the oil's dielectric properties at the same time it can be the reason of higher partial discharge charge accumulation and causing the insulation failure faster than other configurations. It's worth noting that electrical breakdown stresses resulted in carbonization of the oil and a decrease in its flash point compared to virgin oil. Additionally, there was a minor decrease in the viscosity of the electrically tested oil, which can be attributed to a slight reduction in the diffusion coefficient of the oil during exposure to electrical stress.

These findings provide valuable insights into the influence of electrode configurations on the breakdown behavior and dielectric properties of insulating oils, offering essential information for optimizing their performance in electrical applications. This research contributes to the ongoing advancement in this field and may guide future developments and practical applications in enhancing the dielectric properties of insulating oil.

5.2 Suggestions for Future Work

- As nanotechnology is advancing and positively affecting the insulating properties of oils, it's worth noting that while this thesis focused on testing pure mineral oil with the given electrode setups, there is potential for future research to explore the influence of electrodes on the addition of nanoparticles into the oil.

- AC and lighting impulse voltage effects have been observed in this work, DC voltage type can also be used to observe the electrode configuration effects on the insulating properties of oil.
- Due to contaminations in oil, to measure the effect and changes of insulating properties in oil followed by high voltage stress only kinematic viscosity and flash point test have done. Further pour point, fire point, total acid number, antioxidant content, water content, interfacial tension, resistivity, PCA content and dissipation factor test can be performed to analyze the detailed deteriorated propertied of oil.
- Even though we took great care to tightly seal the test containers after the experiments conducted for the thesis, there's still a chance that some of the gases or bubbles produced might have leaked due to differences in pressure inside and outside the containers. To make our findings about the total fault gases more reliable, we can take additional steps to prevent gas leakage. This can be accomplished by improving the sealing of test containers to minimize gas escape during experiments and using an online analyzer to detect dissolved gases (DGA) while collecting oil samples. This approach will help prevent gas loss throughout the process.

REFERENCES

1. Fofana, I., *50 years in the development of insulating liquids.* IEEE Electrical Insulation Magazine, 2013. **29**(5): p. 13-25.
2. Raj, R.A., et al., *An overview of potential liquid insulation in power transformer.* International Journal on Energy Conversion (IRECON), 2020. **8**(4): p. 126-140.
3. Wolmarans, C., et al. *The importance of lightning impulse polarity in transformer liquid insulation*. in *2022 36th International Conference on Lightning Protection (ICLP)*. 2022. IEEE.
4. Kumar, S.S., M.W. Iruthayarajan, and M. Bakrutheen. *Analysis of vegetable liquid insulating medium for applications in high voltage transformers*. in *2014 International Conference on Science Engineering and Management Research (ICSEMR)*. 2014. IEEE.
5. Fofana, I., H. Borsi, and E. Gockenbach, *Fundamental investigations on some transformer liquids under various outdoor conditions.* IEEE transactions on dielectrics and electrical insulation, 2001. **8**(6): p. 1040-1047.
6. Rouse, T., *Mineral insulating oil in transformers.* IEEE Electrical Insulation Magazine, 1998. **14**(3): p. 6-16.
7. Mahanta, D.K. and S. Laskar, *Electrical insulating liquid: A review.* Journal of advanced dielectrics, 2017. **7**(04): p. 1730001.
8. Force, C.T. *Ageing of cellulose in mineral-oil insulated transformers*. in *CIGRE: Paris, France*. 2007.
9. PE, W.H.B. *Analysis of transformer failures*. in *36th Annual Conference of International Association of Engineering Insurers–Stockholm*. 2003.
10. Atalar, F., A. Ersoy, and P. Rozga, *Investigation of effects of different high voltage types on dielectric strength of insulating liquids.* Energies, 2022. **15**(21): p. 8116.
11. Pompili, M., C. Mazzetti, and R. Bartnikas, *Partial discharge pulse sequence patterns and cavity development times in transformer oils under ac conditions.* IEEE Transactions on Dielectrics and Electrical Insulation, 2005. **12**(2): p. 395-403.
12. Korobeynikov, S., et al., *Mechanism of partial discharges in free helium bubbles in transformer oil.* IEEE Transactions on Dielectrics and Electrical Insulation, 2019. **26**(5): p. 1605-1611.
13. Tang, J., et al., *Impact of oil velocity on partial discharge characteristics induced by bubbles in transformer oil.* IEEE transactions on dielectrics and electrical insulation, 2018. **25**(5): p. 1605-1613.
14. Li, J., et al., *Partial-discharge characteristics of free spherical conducting particles under AC condition in transformer oils.* IEEE Transactions on Power Delivery, 2011. **26**(2): p. 538-546.

15. Segal, V., et al. *AC (60 Hz) and impulse breakdown strength of a colloidal fluid based on transformer oil and magnetite nanoparticles*. in *Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No. 98CH36239)*. 1998. IEEE.
16. Thien, Y., et al. *Influence of electrode geometry on the lightning impulse breakdown voltage of palm oil*. in *2018 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. 2018. IEEE.
17. Singh, J., S. Singh, and A. Singh, *Distribution transformer failure modes, effects and criticality analysis (FMECA).* Engineering Failure Analysis, 2019. **99**: p. 180-191.
18. Murugan, R. and R. Ramasamy, *Understanding the power transformer component failures for health index-based maintenance planning in electric utilities.* Engineering Failure Analysis, 2019. **96**: p. 274-288.
19. de Faria Jr, H., J.G.S. Costa, and J.L.M. Olivas, *A review of monitoring methods for predictive maintenance of electric power transformers based on dissolved gas analysis.* Renewable and sustainable energy reviews, 2015. **46**: p. 201-209.
20. Berg, H.-P. and N. Fritze, *Reliability of main transformers.* Reliability: Theory & Applications, 2011. **6**(1 (20)): p. 52-69.
21. Peng, Z., et al., *Ion electric propulsion system electric breakdown problems: causes, impacts and protection strategies.* IEEE Access, 2023.
22. Mc Brien, C. and S. Heltzel. *Insulation resistance of dielectric materials under environmental testing*. in *IPC APEX-EXPO Proceedings*. 2013.
23. Xing, Y., et al., *Defects and failure types of solid insulation in gas-insulated switchgear: In situ study and case analysis.* High Voltage, 2022. **7**(1): p. 158-164.
24. Rao, S., *Influence of environmental factors on component/equipment reliability.* 1998.
25. Beavis, E., *Some developments in the routine pressure-testing of high-voltage cables.* Journal of the Institution of Electrical Engineers, 1928. **66**(382): p. 1086-1097.
26. Adejumobi, I., *Dielectric Strength, Breakdown Voltage and Acidity Test with Respect to Transformer Insulating Oil.* Advanced Materials Research, 2009. **62**: p. 120-125.
27. Beroual, A. *Pre-breakdown mechanisms in dielectric liquids and predicting models*. in *2016 IEEE Electrical Insulation Conference (EIC)*. 2016. IEEE.
28. Hembrom, S., *Analysis of aged insulating oil for early detection of incipient fault inside the high voltage equipment*. 2013.
29. Zhang, X. and E. Gockenbach, *Asset-management of transformers based on condition monitoring and standard diagnosis.* IEEE Electrical Insulation Magazine, 2008. **24**(4): p. 26-40.
30. Pattanadech, N. and M. Muhr. *Comments on PDIV testing procedure according to IEC 61294*. in *2017 IEEE 19th international conference on dielectric liquids (ICDL)*. 2017. IEEE.
31. Wu, J., et al., *Measuring method for partial discharges in a high voltage cable system subjected to impulse and superimposed voltage under*

laboratory conditions. International Journal of Electrical Power & Energy Systems, 2020. **115**: p. 105489.

32. Kuffel, E., W.S. Zaengl, and J. Kuffel, *Chapter 1 - Introduction*, in *High Voltage Engineering Fundamentals (Second Edition)*, E. Kuffel, W.S. Zaengl, and J. Kuffel, Editors. 2000, Newnes: Oxford. p. 1-7.
33. Kuffel, E., W.S. Zaengl, and J. Kuffel, *Chapter 7 - Non-destructive insulation test techniques*, in *High Voltage Engineering Fundamentals (Second Edition)*, E. Kuffel, W.S. Zaengl, and J. Kuffel, Editors. 2000, Newnes: Oxford. p. 395-459.
34. Arii, K. and I. Kitani, *Bubble generation in liquid hydrocarbon in divergent fields.* Japanese journal of applied physics, 1984. **23**(1R): p. 49.
35. Beroual, A. and R. Tobazeon, *Prebreakdown phenomena in liquid dielectrics.* IEEE transactions on electrical insulation, 1986(4): p. 613-627.
36. Kattan, R., A. Denat, and O. Lesaint, *Generation, growth, and collapse of vapor bubbles in hydrocarbon liquids under a high divergent electric field.* Journal of Applied Physics, 1989. **66**: p. 4062-4066.
37. Klimkin, V. and S. Korobeynikov, *Impulse breakdown of liquids*. 2007: Springer Science & Business Media.
38. Lesaint, O. and R. Tobazeon, *Streamer generation and propagation in transformer oil under AC divergent field conditions.* IEEE transactions on electrical insulation, 1988. **23**(6): p. 941-954.
39. Bartnikas, R. *Nature of partial discharges and their measurement*. in *Conference on Electrical Insulation & Dielectric Phenomena—Annual Report 1987*. 1987. IEEE.
40. Boggs, S.A., *Partial discharge: overview and signal generation.* IEEE Electrical Insulation Magazine, 1990. **6**(4): p. 33-39.
41. Mazzetti, C., M. Pompili, and R. Schifani. *A comparative evaluation of partial discharge inception voltage of power transformer liquids*. in *Conference Record of the 1988 IEEE International Symposium on Electrical Insulation*. 1988. IEEE.
42. Pompili, M., C. Mazzetti, and E. Forster, *Partial discharge distributions in liquid dielectrics.* IEEE transactions on electrical insulation, 1992. **27**(1): p. 99-105.
43. Pompili, M., C. Mazzetti, and R. Schifani. *Partial discharge amplitude distribution of power transformer oils*. in *IEEE International Symposium on Electrical Insulation*. 1990. IEEE.
44. Pompili, M., C. Mazzetti, and R. Bartnikas, *Phase relationship of PD pulses in dielectric liquids under ac conditions.* IEEE Transactions on Dielectrics and Electrical Insulation, 2000. **7**(1): p. 113-117.
45. Bolliger, D. and S. Boggs, *Partial discharge based diagnostics for impurities in insulating fluid.* IEEE Transactions on Dielectrics and Electrical Insulation, 2013. **20**(5): p. 1659-1668.
46. Rodrigo Mor, A., et al., *A new design of a test platform for testing multiple partial discharge sources.* International Journal of Electrical Power & Energy Systems, 2018. **94**: p. 374-384.

47. Bolliger, D. and S. Boggs. *Influence of chemical composition on partial discharge characteristics in hexadecane*. in *2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*. 2012. IEEE.
48. Pompili, M., C. Mazzetti, and R. Bartnikas, *Comparative PD pulse burst characteristics of transformer type natural and synthetic ester fluids and mineral oils.* IEEE Transactions on Dielectrics and Electrical Insulation, 2009. **16**(6): p. 1511-1518.
49. Liu, Z., et al. *Partial discharge behaviour of transformer liquids and the influence of moisture content*. in *2014 IEEE 18th international conference on dielectric liquids (ICDL)*. 2014. IEEE.
50. Martin, D., et al., *An overview of the suitability of vegetable oil dielectrics for use in large power transformers.* Euro TechCon, 2006: p. 4-23.
51. Hopkinson, P., et al. *Progress report on natural esters for distribution and power transformers*. in *2009 IEEE Power & Energy Society General Meeting*. 2009. IEEE.
52. Stockton, D.P., et al. *Natural ester transformer fluids: Safety, reliability & environmental performance*. in *2007 IEEE Petroleum and Chemical Industry Technical Conference*. 2007. IEEE.
53. Amanullah, M., et al. *Analyses of physical characteristics of vegetable oils as an alternative source to mineral oil-based dielectric fluid*. in *IEEE International Conference on Dielectric Liquids, 2005. ICDL 2005.* 2005. IEEE.
54. Binns, D. and K. Yoon, *Comparison between insulating properties of transformer oil and a low-flammability ester Midel 7131.* IEE Proceedings A (Physical Science, Measurement and Instrumentation, Management and Education, Reviews), 1982. **129**(3): p. 182-185.
55. Perrier, C. and A. Beroual, *Experimental investigations on insulating liquids for power transformers: Mineral, ester, and silicone oils.* IEEE Electrical Insulation Magazine, 2009. **25**(6): p. 6-13.
56. Lesaint, O., et al. *Streamer propagation and breakdown under AC in mineral oil for gaps up to 80 cm*. in *ICDL'96. 12th International Conference on Conduction and Breakdown in Dielectric Liquids*. 1996. IEEE.
57. Trinh, N.G., C. Vincent, and J. Regis, *Statistical dielectric degradation of large-volume oil-insulation.* IEEE Transactions on Power Apparatus and Systems, 1982(10): p. 3712-3721.
58. Fleszyński, J., B. Lutyński, and J. Skowronński, *Effect of impurities on the breakdown of insulating oil in long gaps.* Journal of Electrostatics, 1979. **7**: p. 47-55.
59. Megahed, I. and A. Zaky, *Effect of electrode material, oxygen and organic additive on the breakdown strength of mineral oil under nonuniform fields.* Journal of Electrostatics, 1982. **12**: p. 345-351.
60. Endicott, H. and K. Weber. *Electrode area effect for the impulse breakdown of transformer oil*. in *1956 Conference on Electrical Insulation*. 1956. IEEE.
61. Kok, J.A., *Electrical breakdown of insulating liquids.* (No Title), 1961.
62. Zaky, A., et al., *Electrical breakdown of mineral oil under uniform fields.* Journal of Physics D: Applied Physics, 1977. **10**(13): p. 1761.

63. Weber, K. and H. Enditott. *Extremal area effect for large-area electrodes for the electric breakdown of transformer oil*. in *1956 Conference on Electrical Insulation*. 1956. IEEE.
64. Guerbas, F., et al., *Barrier effect on breakdown of point-plane oil gaps under alternating current voltage.* Generation, Transmission & Distribution, IET, 2010. **4**: p. 1245-1250.
65. El-Dine, M.Z. and H. Tropper, *The electric strength of transformer oil.* Proceedings of the IEE-Part C: Monographs, 1956. **103**(3): p. 35-45.
66. Hancox, R. and H. Tropper, *The breakdown of transformer oil under impulse voltages.* Proceedings of the IEE-Part A: Power Engineering, 1958. **105**(21): p. 250-262.
67. Carraz, F., P. Rain, and R. Tobazeon, *Particle-initiated breakdown in a quasi-uniform field in transformer oil.* IEEE transactions on dielectrics and electrical insulation, 1995. **2**(6): p. 1052-1063.
68. Wiegand, W., C. Boggs, and D. Kitchin, *Effect of carbon black on insulating oils.* Industrial & Engineering Chemistry, 1931. **23**(3): p. 273-276.
69. CIGRE, T., *Brochure 157: Effect of particles on transformer dielectric strength.* Paris, France, 2000.
70. Krins, M., H. Borsi, and E. Gockenbach. *Impact of carbon particles on the electrical strength of different solid/liquid interfaces in a non-uniform field*. in *Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No. 98CH36239)*. 1998. IEEE.
71. Rain, P., et al., *Behavior of streamers under divergent AC fields in transformer oils at large gaps.* IEEE transactions on electrical insulation, 1991. **26**(4): p. 715-725.
72. Cevallos, M., et al. *Bubble dynamics and channel formation for cathode initiated discharges In Transformer Oil*. in *2005 IEEE Pulsed Power Conference*. 2005. IEEE.
73. Itahashi, S., et al. *The effect of the state of bound water in aged transformer oil on conductivity*. in *Proceedings of 1999 IEEE 13th International Conference on Dielectric Liquids (ICDL'99)(Cat. No. 99CH36213)*. 1999. IEEE.
74. Chandler, D., *Hydrophobicity: Two faces of water.* Nature, 2002. **417**(6888): p. 491-491.
75. Oommen, T. and S. Lindgren. *Bubble evolution from transformer overload*. in *2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No. 01CH37294)*. 2001. IEEE.
76. Clark, F., *The role of dissolved gases in determining the behavior of mineral insulating oils.* Journal of the Franklin Institute, 1933. **215**(1): p. 39-67.
77. Martin, D. and Z. Wang. *A comparative study of the impact of moisture on the dielectric capability of esters for large power transformers*. in *2006 IEEE conference on electrical insulation and dielectric phenomena*. 2006. IEEE.

78. Borsi, H., *Dielectric behavior of silicone and ester fluids for use in distribution transformers.* IEEE transactions on electrical insulation, 1991. **26**(4): p. 755-762.
79. Brinkmann, K. and M. Beyer, *Uber die Hochvakuum-Trocknung und—Entgasung von Isolierolen fur Hochstspannungs-kabel.* Elektrotech. Z., 1960. **81**: p. 744-749.
80. Miners, K., *Particles and moisture effect on dielectric strength of transformer oil using VDE electrodes.* IEEE transactions on power apparatus and systems, 1982(3): p. 751-756.
81. Wang, X. and Z. Wang. *Particle effect on breakdown voltage of mineral and ester based transformer oils*. in *2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*. 2008. IEEE.
82. Hayakawa, N., et al., *Breakdown mechanism of liquid nitrogen viewed from area and volume effects.* IEEE Transactions on Dielectrics and Electrical Insulation, 1997. **4**(1): p. 127-134.
83. Kattan, R., A. Denat, and O. Lesaint, *Generation, growth, and collapse of vapor bubbles in hydrocarbon liquids under a high divergent electric field.* Journal of applied physics, 1989. **66**(9): p. 4062-4066.
84. Lesaint, O., et al., *Streamer propagation and breakdown under ac voltage in very large oil gaps.* IEEE transactions on dielectrics and electrical insulation, 1998. **5**(3): p. 351-359.
85. Top, T. and A. Lesaint, *Streamer initiation in mineral oil. Part II: Influence of a metallic protrusion on a flat electrode.* IEEE transactions on dielectrics and electrical insulation, 2002. **9**(1): p. 92-96.
86. Felici, N., *High-field conduction in dielectric liquids revisited.* IEEE Transactions on Electrical Insulation, 1985(2): p. 233-238.
87. Uamran, D.A., et al., *Simulation and Study the Effect of the Channel Radius Streamer Discharge Propagation, and Characteristics in Water Filled Gap.* NeuroQuantology, 2020. **18**(2): p. 37.
88. Lesaint, O. and R. Tobazeon, *Study of the generation by sharp electrodes of a gaseous phase in dielectric liquids subjected to high ac or step voltages.* IEEE Transactions on Electrical Insulation, 1985(2): p. 269-273.
89. Danikas, M. *Study of some factors affecting the breakdown strength of transformer oil*. in *1988 Fifth International Conference on Dielectric Materials, Measurements and Applications*. 1988. IET.
90. Hosticka, C., *Dependence of uniform/nonuniform field transformer oil breakdown on oil composition.* IEEE Transactions on Electrical Insulation, 1979(1): p. 43-50.
91. Asem, A.S. and A. Howe. *Drying of power-transformer insulation*. in *IEE Proceedings C (Generation, Transmission and Distribution)*. 1982. IET.
92. Golovan', G., et al., *Water solubility in transformer oils with various hydrocarbon compositions.* Chemistry and technology of fuels and oils, 1984. **20**: p. 387-391.
93. Palmer, S. and W. Sharpley. *Electric strength of transformer insulation*. in *Proceedings of the Institution of Electrical Engineers*. 1969. IET.

94. Clark, F., *Water solution in high-voltage dielectric liquids.* Electrical Engineering, 1940. **59**(8): p. 433-441.
95. Du, Y., et al., *Moisture solubility for differently conditioned transformer oils.* IEEE transactions on Dielectrics and Electrical Insulation, 2001. **8**(5): p. 805-811.
96. Fofana, I., H. Borsi, and E. Gockenbach. *Moisture uptake of mineral oil at different air relative humidities and temperatures*. in *2000 Annual Report Conference on Electrical Insulation and Dielectric Phenomena (Cat. No. 00CH37132)*. 2000. IEEE.
97. Jin, H., *Dielectric strength and thermal conductivity of mineral oil based nanofluids.* Delft University of Technology, 2015: p. 1-170.
98. Nelson, J. and I. Hashad, *Evidence for cavitation in fluorocarbon liquids subjected to alternating electric fields.* Journal of Physics D: Applied Physics, 1976. **9**(2): p. 203.
99. Singh, B., et al., *Prebreakdown processes in electrically stressed insulating liquids.* Journal of Physics D: Applied Physics, 1972. **5**(8): p. 1457.
100. Toriyama, Y., T. Sato, and H. Mitsui, *Dielectric breakdown of insulating liquids.* British Journal of Applied Physics, 1964. **15**(2): p. 203.
101. Zaky, A., et al., *Electrical breakdown of mineral oil under non-uniform fields.* Journal of Physics D: Applied Physics, 1976. **9**(15): p. 2287.
102. Frayssines, P., et al. *Prebreakdown and breakdown phenomena under uniform field in liquid nitrogen*. in *Proceedings of 2002 IEEE 14th International Conference on Dielectric Liquids. ICDL 2002 (Cat. No. 02CH37319)*. 2002. IEEE.
103. Frayssines, P.-E., et al., *Prebreakdown and breakdown phenomena under uniform field in liquid nitrogen and comparison with mineral oil.* IEEE transactions on dielectrics and electrical insulation, 2003. **10**(6): p. 970-976.
104. Beroual, A., et al., *Propagation and structure of streamers in liquid dielectrics.* IEEE Electrical Insulation Magazine, 1998. **14**(2): p. 6-17.

LIST OF PUBLICATIONS

Exploring the Impact of Electrode Configurations on Mineral Oil: A Comprehensive Analysis of AC Breakdown Voltage, Partial Discharge, and Chemical Changes

Journal: IEEE Access

Status: Under Review