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Pre-breakdown phenomena in ester-based fluids for potential application in transformers serving in cold climatic regions

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RÉSUMÉ

Depuis quelques années, les contraintes environnementales sont devenues des éléments majeurs à prendre en compte dans le choix des liquides isolants. C'est pourquoi la recherche sur les isolants liquides biodégradables, alternatives aux huiles minérales, connait un engouement. Malgré l'avancée des connaissances sur les huiles biodégradables, l'application d'esters à bas point d'écoulement pour l'isolation des transformateurs exploités dans les régions à climat froid reste un défi. Malgré de nombreuses caractéristiques positives des esters, des études concernant la propagation des « streamers » ont indiqué qu'elle se comporteraient moins bien que les huiles minérales. Pour contribuer à l'avancée des connaissances dans ce domaine, les tensions de préclaquage et de claquage d'esters à bas point d'écoulement vieillis thermiquement ont été étudiées. Des essais avec huile minérale ont été réalisés en parallèle à des fins de comparaison. Les mesures de tension de claquage ont été effectuées (dans une configuration d'électrode pointe-plan), à différentes durées de vieillissement avec différents rayons de l'électrode haute tension (HT) sous tension alternative. Cette approche permet d'étudier l'effet des impuretés chimiques (sous-produits du vieillissement) évaluées par certaines propriétés physico-chimiques (acidité, nombre de particules, turbidité et spectroscopie UV) sur les caractéristiques de décharges partielles (DP) et de dégradation.

L'analyse est effectuée pour des liquides ayant un point d'écoulement inférieur à -50°C, une huile minérale (MO) et deux esters synthétiques (SE1 et SE2). Les changements dans les propriétés des décharges telles que la tension seuil d'apparition de décharges partielles (PDIV), la tension d'apparition des décharges streamers, le champ électrique seuil d'apparition des décharges électriques et la tension de claquage, sont rapportés en fonction du rayon de l'électrode HT et du degré de vieillissement. Pour évaluer le niveau de dégradation des liquides, des mesures par spectroscopie UV-visible, de turbidité, du nombre de particules et d'acidité ont été effectuées.

Pour mettre en évidence l'influence du vieillissement sur l'initiation des décharges streamers, des corrélations appropriées ont été rapportées entre les produits dissous, l'acidité et le PDIV. Il est possible d'observer que les propriétés de claquage de SE1 sont meilleures que celles de SE2 et comparables à celles de MO. Ce qui souligne le potentiel d'utilisation du SE1, à tout le moins en ce qui a trait aux phénomènes de pré-claquages. Il est également important de mentionner que l'acidité et la quantité relative des produits dissous évoluent de manière linéaire avec l'apparition des DP et la propagation des décharges *streamers*, indépendamment du rayon de l'électrode HT.
Le calcul du champ électrique d'initiation des décharges dans les fluides isolants est d'un intérêt général pour la conception d'équipements HT remplis de liquide. Étant donné que les processus physiques du claquage ne sont pas encore entièrement compris, les ingénieurs concepteurs pourraient se fier à ces corrélations pour calculer le seuil d'initiation d'une disposition spécifique.

ABSTRACT

In recent years, environmental constraints have become major elements to be considered in the choice of insulating liquids. To address this concern, the present research has been directed towards biodegradable insulation liquid alternatives to mineral oils. Despite the advancement of knowledge on biodegradable oils, the application of low pour point esters in the insulation system of the transformers operating in cold climates remains a challenge. Apart from many positive characteristics of esters, the study of the propagation of "streamers" have indicated the poor performance when compared to mineral oils. To contribute the advancement of knowledge in this field, prebreakdown and breakdown phenomena of thermally aged low pour point esters have been studied. Tests with mineral oil were carried out in parallel for comparison. The breakdown voltage measurements were performed (in a needle-plane electrode configuration), at different aging conditions with different high voltage (HV) electrode tip radii under AC voltage. This allows studying the effect of chemical impurities (aging by-products) as assessed by some physicochemical properties (acidity, particles count, turbidity, and UV spectroscopy) on partial discharges (PD) and breakdown characteristics.

The complete analysis is carried out for the liquids having pour point less than -50°C with those including a mineral oil (MO) and two synthetic ester liquids (SE1 and SE2). Changes in discharge properties such as particle partial discharge inception voltage (PDIV), breakdown-streamers inception voltage, inception electric field, and breakdown voltage are reported as a function of the HV electrode tip radius and aging factor. To assess the level of liquid degradation, UV spectroscopy, turbidity, particle count, and acidity measurements were performed.

To highlight the influence of aging on streamer inception, suitable correlations have been reported between decay products, acidity, and PDIV. It is observed that the breakdown properties of SE1 are better than that of SE2 and comparable to MO. This underlines the potential use of the SE1, at least with regard to pre-breakdown phenomena. Importantly, the acidity and concentration of decay products evolve linearly with PD inception and streamer propagation regardless the tip radius. The calculation of the electrical onset in insulating fluids is of general interest for designing HV liquid filled equipment. As the physical processes of the breakdown are not yet fully understood, design engineers could rely these correlations when calculating the onset strength of a specific design layout.

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LIST OF ABBREVIATIONS

AC – Alternating Current
ASTM – American Society for Testing and Materials
BSIV – Breakdown Streamer Inception Voltage
BDV – Breakdown Voltage
DAQ – Data Acquisition System
DDP – Dissolved Decay Particles
E – Electric field stress
G – Ground
HV – High Voltage
MO – Mineral Oil
NE – Natural Ester
NTU – Nephelometric Turbidity Unit
N1 – Needle 1
N2 – Needle 2
N3 – Needle 3
PC – Personal Computer
PD – Partial Discharge
PDIV – Partial Discharge Inception Voltage
PMT – Photo Multiplier Tube
SE1 – Synthetic Ester 1
SE2 – Synthetic Ester 2
TF – Transformer
TUK – Thermally Upgraded Kraft
UV-VIS – Ultraviolet- Visible

DEDICATION

This thesis is dedicated to the Almighty, my parents and husband.

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I would like to express my sincere gratitude and respect to my research director Prof. Fofana, UQAC and Project manager (industrial collaborator) Dr. P. Picher, IREQ for giving me this opportunity and encouraging me during my Masters. I also thank my co-directors, Prof. S. Brettschneider, UQAC and Dr. Rodriguez Celis, IREQ for their continuous technical support and help during this research. In addition, the technical and editorial support of Dr. Rodriguez Celis, IREQ and Dr. U. Mohan Rao, UQAC are highly acknowledged.

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CO-AUTHORED PUBLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The transformer is considered as one of the most significant equipment in the power system network. For many decades, it is known that the functional existence of oil-immersed power transformers has been used for a wide range of voltages in both distribution and transmission levels. In liquid insulated power transformers, the insulation typically comprises cellulose wrapped conductors immersed in oil. The impregnation of the oil into the empty gaps of the paper aids in increasing the dielectric strength of the transformer insulation. In this type of composite insulating system, there is a chance for two types of electrical faults to occur leading to insulation failure. The first type of failure may evolve in between two windings, which may further cause oil breakdown, creepage breakdown or both. The second type of failure is a partial discharge that does not show any sudden failure between the two windings [1]. However, the continuous partial discharge contributes to disturbing the solid insulation in order to cause failure with time. One of the main reasons to initiate these electrical faults in power transformers is premature aging of oil-paper insulation. Therefore, the power transformer reliability depends on the condition of its insulating system.

Since the nineteenth century, mineral oil (MO) is the most used insulating liquid in power transformers [2]. As an insulating liquid, MO not only increases the dielectric strength of the insulation but also acts as a cooling agent dissipating the heat generated in the core and windings of the transformer. MO advantageous properties, such as thermo-physical and electrical, low cost and wide availability made its existence in all the oil-filled transformers from the beginning of the transformer industry. Nevertheless, its poor biodegradable nature made researchers look for alternative liquids to MO. It is reported that ester based dielectric liquids are potential replicates for mineral oils in transformers [3, 4]. Esters are of two types, namely natural esters (NE) sourced from vegetable oils and synthetic esters (SE), which are synthesized from acids and alcohols. The advantages of ester fluids like biodegradability, high dielectric strength, high fire safety, high moisture absorbance made them a potential alternative to mineral oils [5]. However, some deficient features of natural esters like low oxidation stability and poor viscosity are challenging the application of natural esters in breathing transformers [6]. Therefore, absolute understanding of the ester fluids operational behavior, usage in cold countries and compatibility with other transformer materials of ester fluids is essential. In this study, the prebreakdown and breakdown behavior of low pour point ester liquids have been the emphasized. It is to be mentioned that Hydro-Québec uses the standard CSA-C50-14 (class A) for its choice of insulating liquids according to which the acceptable pour point limit is -46°C. Even though CSA-C50-14 is developed for mineral oils, the specified pour point it is considered for selection of ester liquids for the present research based on pour point. Subsequently, a pour point of -50°C is adopted as a reference for the present research. Commercially available ester fluids having pour point less than -50°C are identified and are referred as low pour point liquids.

Several researchers investigated the prebreakdown and breakdown processes in dielectric liquids and stated that pre-breakdown events known as “streamers” lead the insulating medium to breakdown [1, 7]. This breakdown process is theoretically explained by different theories those including ionization theory, weak link theory, and streamer theory. The details of these theories, while including the research progress in the transformer dielectric liquids, are discussed in the subsequent section.

1.2 AGING AND MONITORING OF INSULATION OIL

Insulating liquid in power transformers play a major role in effective operation of the transformer during the service life. The degradation of the transformer insulation system influences its service life and theoretically its designed life. The preliminary causes for the degradation of the oil/paper insulation system are its decomposition aspects. Degradation process of the insulation system in oil-filled apparatus is governed by the heat, oxygen and moisture. Oxygen may ingress from cellulose or from external environment through breather configurations for non-sealed transformers. Similarly, moisture may also entered from the cellulose fibers or through the external environment. However, for non-sealed units efforts are taken to avoid the interaction of the insulation system with the external air. Heat liberated from the core-winding assembly will adversely affect the life of the insulation system if not dissipated properly in time [8]. In addition, this heat will promote the degradation mechanisms including hydrolysis, oxidation, and the cellulose pyrolysis causing the premature aging of the insulation system.

Further, the electrical stress generates free radicals and initiates ionization in the bulk volume of the oil. These free radicals recombine to produce decay products. The ionization process may increase local dielectric stress in the liquid or around the solid insulation system. This increase in local dielectric stress may lead to partial discharges. It is to be mentioned that all the degradation mechanisms are highly interrelated and produce decay particles either in solid, liquid or gaseous states. The presence of different aging by-products has different detrimental effects on the service life of the transformer. The illustration of the degradation process in insulation system is summarized in Figure 1.

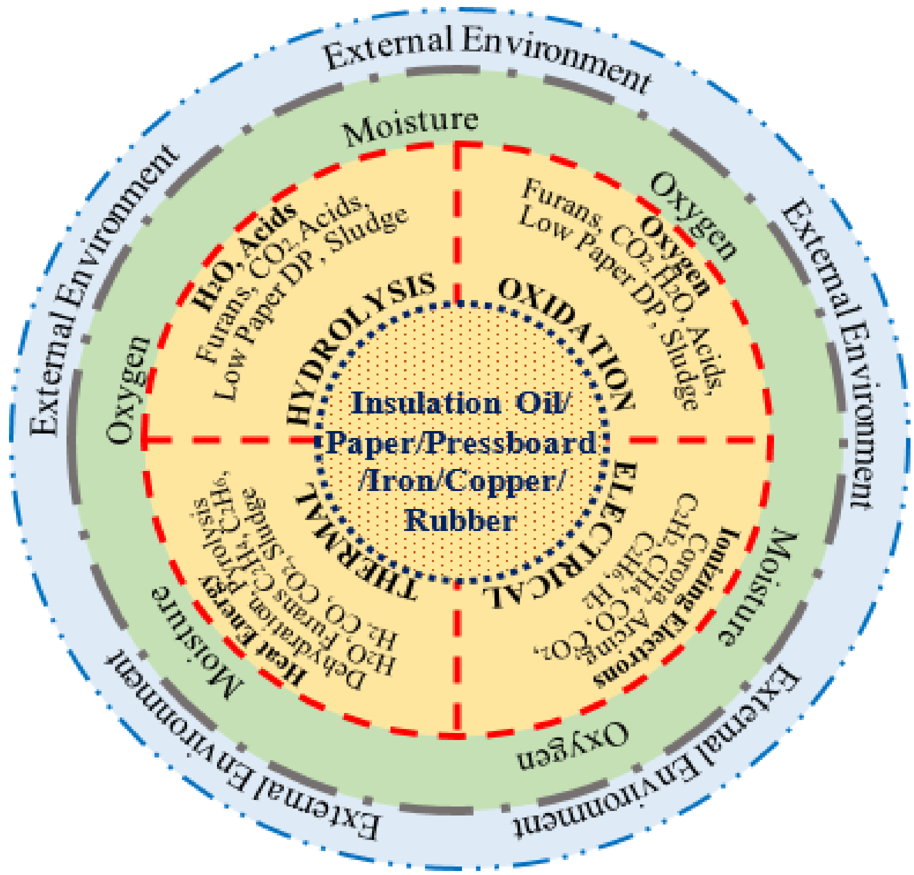


Figure: 1 Representation of insulation degradation in liquid filled transformers [8].

Understanding the degradation process and its consequence (which influence the performance and life of the oil-filled apparatus) is required for transformer condition monitoring. The current state of knowledge on condition monitoring indicates that degradation/aging is associated with a large number of parameters that are interrelated. Thus, periodical monitoring and understanding of a single parameter will not be enough to analyze the degradation condition. Since the direct access to the solid insulation is not possible for an in-service transformer, the insulating liquid is sampled to monitor indirectly the degradation of solid insulation. Thus, an effective insulating liquid with high degree of compatibility with other transformer materials is required. A significant number of researches confirmed the potential use of ester dielectric fluids in transformers [9].

1.3 MOTIVATIONS AND RESEARCH GAP

The pre-breakdown phenomena of mineral insulating oils and ester dielectric fluids have been the focus of research since many years and abundant research data is available in the literature [9-12]. However, to the best of our knowledge, it is observed from the literature survey that, there is no published data on pre-breakdown phenomena of low pour point ester fluids. It is to be recalled that typical synthetic esters are modified to low pour point liquids by adding depressants. Thus, there is a need for understanding the behavior of low pour point liquids for potential applications in cold countries. In addition, the influence of aging by-products on the prebreakdown phenomena has been least emphasized. In the present research, prebreakdown and breakdown phenomena of low pour point liquids while investigating the influence of aging by-products is reported.

This research will provide insulation and design engineers with fundamental background information that may help improving the design of transformers serving in cold regions [13]. It will also be useful for those interested in application of ester fluids for liquid filled transformers serving in cold climatic regions.

1.4 RESEARCH OBJECTIVE

The objective of this project is to study the pre-breakdown processes in low pour point ester fluids for potential applications in transformers serving in cold climatic regions. The influence of oil aging and tip radius of the high-voltage needle electrodes on the pre-breakdown process are evaluated. In addition, acidity, turbidity, dissolved decay products, and particle count measurements are performed to monitor the degree of oil's aging. This allows understanding the effect of aging by-products on the partial discharge inception voltage (PDIV). For comparative analysis, mineral oil has been included in the test loop. The investigations reported in this study aim at comparative analyses of streamers characteristics.

1.5 RESEARCH METHODOLOGY

The research methodology used in this work is presented in Figure 2.

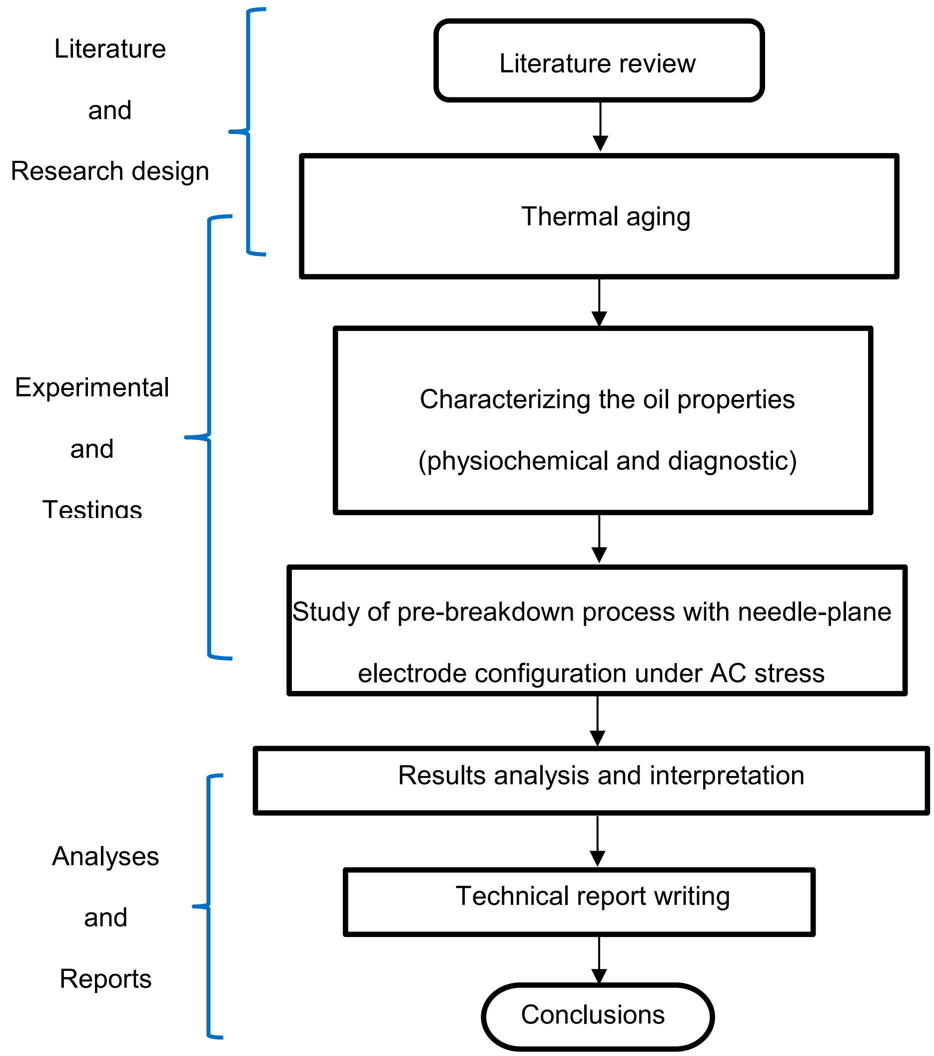


Figure: 2 Methodology of the present research.

This master research work started with an initial literature survey which helped finding out the research gaps in the field of interest. This further aided in framing the research objectives for this study. Later, the pretreatment and thermal aging of the fluid samples (Insulating liquids and Paper) has been performed. The physicochemical characterization of non-aged and aged liquid samples were carried out. In addition, the electrical tests were performed for all the liquid samples (Non-aged and aged) with a needle-plane electrode configuration under ac stress. This is further, followed by the analysis and interpretation of the obtained results. The interpretations and the conclusion drawn were reported in this thesis along with the appropriate scientific references.

1.6 THESIS ORGANIZATION

To present the research work carried out in this project, the present thesis is organized in the following chapters.

Chapter 1 (*Introduction*): A brief introduction to the subject of the present research focus is presented. This chapter also presents the research motivation, methodology, and objectives of the present project.

Chapter 2 (*Literature Survey*): In this chapter, a detailed literature survey on the prebreakdown phenomena in ester fluids is reported. In addition, the fundamentals of streamer theories, streamer properties and streamer characteristic voltages, influence of electrode geometry and temperature on streamers is highlighted.

Chapter 3 (*Experimental and Methods*): This chapter deals with the presentation of the materials, methods, and practices adopted for conducting the experimental investigations.

Chapter 4 (*Results and Discussion*): The experimental results of the electrical and physicochemical characterizations are discussed in this chapter. The observations, hypothesis, and suitable correlations are also discussed in this chapter.

Finally, the conclusions made from the present research and list of references are presented.

1.7 SUMMARY

In chapter 1, a general introduction to the topic of research is presented within indication to the importance of the present research. As the current thesis is focused on the transformer insulation, the general outline of insulation degradation and importance to monitor the insulation degradation are discussed. In addition, motivation to the present research and research gaps vis-à-vis the literature on the topic of research are presented. Furthermore, the intent of the current research and the methodology adopted to meet the proposed objective has been outlined. A brief note on the chapters of this thesis is discussed highlighting the thesis organization.

CHAPTER 2

LITERATURE REVIEW ON PREBREAKDOWN IN ESTERS

2.1 BACKGROUND ON BREAKDOWN IN INSULATING LIQUIDS

Electric discharge is a phenomenon characterized by the sudden release and transmission of electric energy through an insulating medium (solid, liquid or gas) in between any two electrodes in an applied electric field. This continuous electric discharge in insulating medium builds a bridge in between the two electrodes which leads to a complete breakdown. The electric breakdown in insulating liquid involves many stages. The process leading to it was described into various theories by many early researchers, which is discussed in the following sections [14, 15]. Any advent of failure in the transformer insulation shows major effect on the whole power system network as well as the environment. The predominant scope of failure in power transformers is due to the insulation breakdown. Substantially, the breakdown in composite (oil - paper) insulation in power transformers depends on various parameters such as, the nature and condition of the electrodes, the physicochemical properties of the dielectric liquids, the presence of voids, fibers, chemical impurities, moisture and irregular surfaces inside the transformer [15]. These imperfections give rise to the release and transmission of electric charges within the insulating medium, thus causing a deterioration. The breakdown phenomena also depend on the chemical composition of liquids. In other words, this behavior is different for ester liquids and mineral oils [3, 4, 11]. The detailed differences between mineral oils and ester liquids are discussed in [2 - 5, 8, 9]. Hence, there is a demand in understanding the significance of the pre-breakdown phenomena in different insulating liquids while respecting the operating conditions.

2.2 BREAKDOWN THEORIES

Understanding the fundamental theoretical causes of insulating liquids breakdown, that is, the conditions necessary for electron avalanche formation, are important to the proper design of practical HV liquid-filled equipment. A large number of papers and books on the prebreakdown and breakdown of insulating liquids are available.

A review of the present state of knowledge of the insulating liquids discharge can be found in [1, 7, 10 -15]. However, to ease interpretation of the measurements presented in this thesis, a short review including inception, streamer propagation and spark breakdown is presented.

2.2.1 IONIZATION THEORY

Ionization theory predicts that under high electric field electron energy can be increased to ionization level. Once accelerated under the electric field, this tends to collision-ionization process which may lead to a complete breakdown. This theory is advocated in the early 1940s to address the breakdown mechanism concerning the electrical insulating liquids. The postulates of this theory claimed that breakdown in insulating fluids is due to the collisions between micro particles of the liquid. It also implies that electrons with high ionization potential are capable of undergoing a high rate of collisions, thus leading to rapid breakdown. On the other hand, it is reported that the ionization due to collision cannot survive in insulating liquids even with increasing voltage [16]. One of the main reasons is that the existence of the free electrons in insulating liquids are noticeably rare since the electrons are bound to the liquid molecules or in the form of negative ions. Hence, there is negligible scope for the existence of free electrons in insulating liquids.

2.2.2 WEAK-LINK THEORY OR STRESSED OIL VOLUME THEORY

Characterization of breakdown in insulating liquids is not feasible with a single parameter so-called collision. Hence, the proposal of weakest-link theory was created [1]. It is not possible to find a pure dielectric liquid, however, there is a minimal trace of impurities present in liquid which are left by conduction and breakdown in the commercial oils. Therefore, this theory then introduced that the breakdown strength of the dielectric liquid is determined by the “largest possible impurity” or “weak link. So, this theory brings a note that the breakdown in liquid gets initiated by the weakestlinks present in the liquid such as rough surfaces, sharp edges caused due to the internal deformations. According to the literature, it is known that the breakdown strength of an insulating liquid decreases with increasing stresses in volume [17].

However with more research investigations, it was reported that the breakdown in liquids is also attributable to many other parameters (dissolved gases, viscosity, chemical additives, moisture content, the electrode geometry, the type of the applied voltage, the temperature and hydrostatic pressure and other impurities in the liquid) [18]. These factors are highly interlinked and are variable with test conditions or operation conditions. However, the overall impact of these factors highly influences the dielectric strength of the insulating fluid. Hence, assessment of the breakdown voltage of a dielectric fluid for one particular test condition may not be the global value as it is highly related to test conditions and external factors [16].

2.2.3 STREAMER THEORY

The streamer theory came to light to interpret the breakdown mechanisms in liquid dielectrics. Earlier in the 1970s, the streamer theory approached by saying that the breakdown voltages in liquids depends on the adequate amount of the pressure to generate vapor bubble at the stressed area of the liquid volume. It is also believed that the formation of gas bubbles is responsible for the initiation of the breakdown process in insulating liquids. Krasucki in 1966 quotes that under definite experimental conditions there is a presence of the initiation of the vaporization [19]. When the liquid is subjected to an adequate amount of high electric field, which leads to the growth in zero pressure points in the liquid which, ultimately gives rise to the initiation of a hollow cavity. The bombardment of electrons inside the cavity walls induce vaporization in the liquid [19]. This shows some evidence that the process of gas or vapor bubble formation is responsible for breakdown in highly stressed liquids. The authors clearly reported the influence of thermal bubbles on breakdown strengths of the liquids from the viewpoint of volume and area effects. It is also found that the breakdown phenomena in insulating liquids is believable of generating thermal bubbles prior to the complete breakdown [20].

The rapid development in technology and digitalization improved the quality of analyzing the pre-breakdown events. The contemporary optical methods with the high-speed imaging techniques facilitated the research exploration in breakdown mechanisms of insulating liquids. Additionally, these experimental techniques fetched an evident support for bubble theory [21]. Streamer theory is an extension of the bubble theory, which was introduced after the 1980s [1]. This theory also surmises that a small gas or vapor bubble was spotted at the needle electrode tip in the non-homogenous field generated by the electrode configuration (needle plane) as an initiation to breakdown [22, 23]. Vapor bubble is reviewed as a general domain, in which the breakdown processes is same as in that of air. The continuous and progressive collision-ionization processes elongate the bubble thus, bridges the electrode gap and ultimately causing breakdown. The breakdown of this expanded or lengthened bubble channel is recognized as the main cause of breakdown in insulating liquids [1, 24]. With global acceptance and time, the streamer theory has become more popular and governing the breakdown mechanisms in the insulating liquids. The breakdown mechanism in this theory is all about the initiation and propagation of the streamer, which finally leads to a complete breakdown under applied field. There is a large number of factors influencing the initiation and propagation of the streamers in transformer oils which are discussed in the following sections. Prior to these factors, the various stages involved in initiation, propagation and breakdown in insulating oils are represented by the pre-breakdown events called as ‘streamers’ [25].

2.3 SIGNIFICANT STREAMER PROPERTIES

The concern on the alternative ester liquids namely natural ester (NE) and synthetic ester (SE) as a substitute for mineral oil (MO) in high-voltage power transformers has been progressing since the 1990s [2]. As illustrated in the above, esters oils are the potential substitutes for traditional mineral oils because of their eco-friendly properties, good dielectric properties and better fire safety comparatively [2, 26]. Despite these advantages, the extension of the ester oil application in power transformers has been a challenging issue [27]. A good insulating system for a large oil-immersed power transformer must be designed with all the care to protect against any insulation failure. Therefore, as highlighted in the above sections, it is necessary to study the pre-breakdown and breakdown characteristics of the insulating liquids along with the physio-chemical properties to obtain a better alternative insulating liquid for power transformer insulation. A large number of research data is available on MO in this topic in the past three decades [28-30]. The research on alternatives of MO is also dominantly progressive in recent years on pre-breakdown and breakdown phenomenon studies. It is noticed that the chemical composition of the dielectric liquid has an influence on its pre-breakdown and breakdown characteristics. As the chemical composition of ester oils (NE & SE) is not the same as the mineral oils, the streamer characteristics in these dielectric liquids (MO NE & SE) are dissimilar.

2.3.1 STREAMER INCEPTION VOLTAGE

The pre-breakdown characteristic investigations under different applied fields (DC, AC, impulse), were carried out by many researchers. It is quoted that natural esters reveals an easier streamer initiation and propagation as compared to traditional mineral oils [11,16,18, 25 and 31]. It is reported that the streamer inception voltages of natural esters at 8 mm and 18 mm needle-plane electrode gaps is about 50% lower than the streamer inception voltage in mineral oil [27]. Furthermore, streamer initiation is also noticed to form rapidly in case of synthetic esters when compared to mineral oils under non-uniform fields [27]. Many research investigations on this subject aimed to compare streamer characteristics (length, velocity, shape, area, and mode) of natural and synthetic esters with that of mineral oils [25, 32]. Even though inception voltages of esters (synthetic and natural) and mineral oils are comparable, streamer propagation in ester fluids under standard impulse voltage is higher while witnessing dense streamer branches [25, 33]. Experiments on mineral oil, natural esters, and synthetic esters were carried out to study the pre-breakdown phenomenon under standard lighting impulse voltage (1.2/50 μs) at both polarities (positive and negative). Many researchers analyzed the results individually regarding the streamer mechanisms and reported that with increasing tip radius and diameter of the high-voltage electrode, the threshold voltage increases. This shows that the tip radius of the point electrode has more impact on the threshold voltage [34-37]. The threshold voltage or the inception voltage is the value below which there is no initiation of the streamer. After streamer initiation, with the increase in the voltage irrespective of polarities, the streamers start to propagate from the tip of the point electrode (high field area) towards the ground electrode through the gap.

2.3.2 AFFECT OF POLARITY ON STREAMERS CHARACTERISTICS

The voltage polarity influences the streamer structure and velocity in non-homogeneous electric fields [11, 12]. Besides, the positive and negative streamers travel through different modes while moving towards the ground electrode [33]. With respect to their velocities and structure, positive streamers are classified into three modes (first, second and third), while the negative streamers have only two modes (first and second) [11, 25 and 36]. As per the literature, the inception voltage of the streamer's second mode is 10 times higher than that of the streamer's first mode [33]. High stress between the electrodes gives roots to the extreme high-speed streamer's third mode whose shape is slightly filamentary. The negative streamers are classified into two modes: first and second. Due to the polarity change of applied impulse voltage, the negative streamer's first mode comes into view. The inception voltage of negative streamers' first mode is slightly more than that of the positive streamers' first mode. Under low electric fields, the negative streamer structure looks like a leafless treetop. With additional increase in voltage, the streamer propagates at high speed and intensity. At higher voltages, the structure of the negative streamer's changes to a compact bushy like and the negative streamer's second mode can only be detected in the electrode gaps higher than 37 mm [11].

2.3.3 STREAMER STOPPING LENGTH

The streamers initiate and propagates towards the high-field region below the value of the breakdown voltage. Eventually, the propagation length comes to an end at some point of time. This length is calculated from the results recorded by the multi-channel high-speed camera. The propagation length is measured from the extreme end of the streamer to the tip of the needle electrode, which in turn, is termed as a stopping length of the streamer as illustrated in Figure 3 [25].

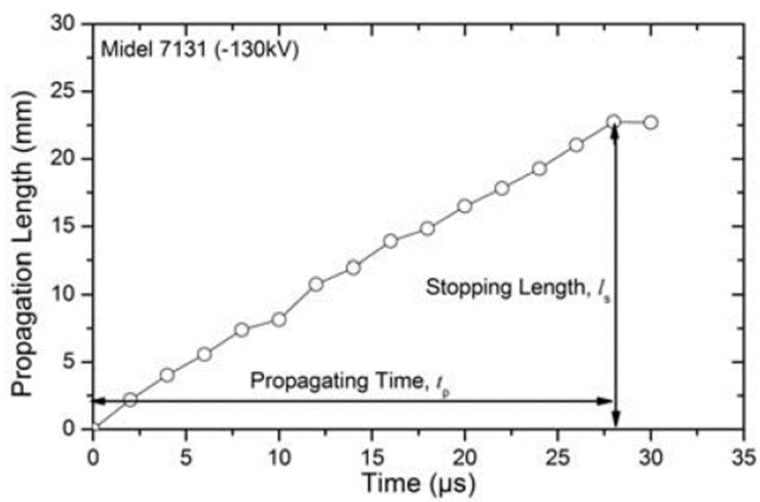
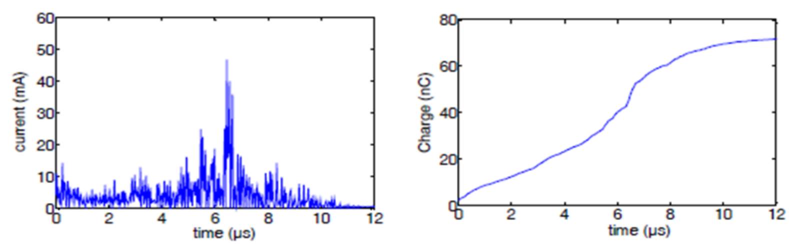


Figure: 3 Streamer stopping length in synthetic ester [25].

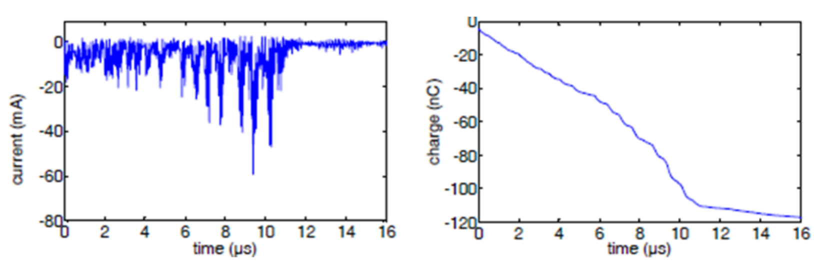
According to the literature, the stopping lengths of the streamers were observed to depend on the liquid’s chemical composition and the polarity of the voltage (positive and negative) [25, 34]. The final lengths of the streamers in both MO and esters (NE & SE) were examined for both polarities, which indicates that the stopping length increases with increasing applied field. The stopping length of the positive streamers are higher when compared to the negative streamer with increasing voltage [25, 34]. The final lengths of the positive streamers have been found to be ten times longer in vegetable-based esters when compared to that of crude-oil based mineral oils [38]. These observations show that the physicochemical mechanisms that takes place in both polarities are dissimilar [39]. The voltage drop is initiated in between the needle electrode tip and the streamer's head when the streamers tend to stop. The breakdown voltages in esters and MO are also attributable to electrode geometry and the applied voltages. Therefore, it is stated [34] that the positive streamers are comparatively more conducting by deriving relation between the stopping length and the longitudinal electric field in the streamer channel with the help of the change in voltage [34]. In addition, it is accepted that the highly conducting streamers are fast propagating [34]. The stopping length and the electrode geometry are interrelated as the stopping length and the velocity of the streamer decreases with the increase in the electrode gap [40]. Besides, it is observed that the stopping length is shorter in mineral oil than in vegetable-based esters [38].

2.3.4 STREAMER CURRENT AND CHARGE

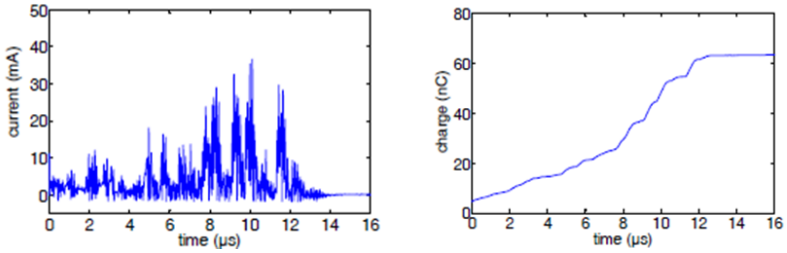
The streamer current presents similar shape in all liquids irrespective of the voltage polarity [17, 34, and 41]. According to [41], the charge corresponding to the current changes in steps and the changes in the current pulses are very small, this indicated that the streamer propagation takes place in steps with higher velocities as presented in the Figure 4 (a), (b), (c) and (d) [34].



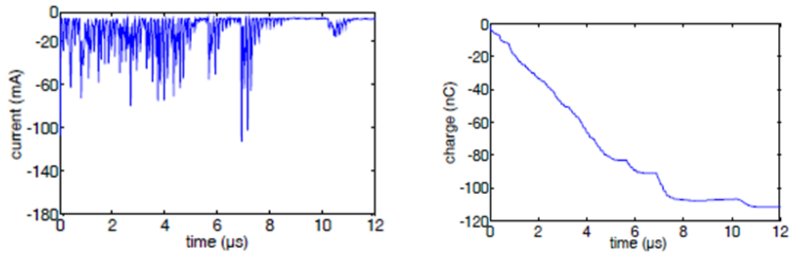
(a) Positive streamer current and charge in mineral oil



(b) Negative streamer current and charge in mineral oil



(c) Positive streamer current and charge in vegetable oil



(d) Negative streamer current and charge in vegetable oil

Figure: 4 Illustration of streamer current and charge in different liquids for positive and negative polarities [34].

It is also found that the charge of the positive streamer is higher than that of the negative one for a given applied voltage. In addition, the negative streamer charge is higher in vegetable oils when compared to that in MO [34].

2.3.5 STREAMER VELOCITY

In general, the velocity is defined as the rate of change of distance with respect to time. In streamer processes, the velocity of the streamer propagation is an influential characteristic in understanding the reciprocity between a partial discharge and a surface of the insulating liquid [42]. This influencing streamer property was analyzed using the results obtained from the modern optical methods with the help of the ultra-high-speed framing camera. The propagation velocity (Vp) can be deduced from the stopping length (ls) and the propagation time (ts) as $Vp = \frac{ls}{ts}$. The time (ts) can be evaluated from the observations of streamer current and charge [11, 25, 34 and 35]. It is clear from

[9] that the propagation velocity increases with any increase in the applied voltage irrespective to the polarity. Besides this, the streamer velocity depends on the inter-electrode gap. Considering the case of complete breakdown, the axial velocity (Vp) can be calculated as the ratio of gap distance and time (ts) assuming the streamer is claimed to travel with predictable constant velocity from the results obtained in [25]. It was observed that the propagation velocities of streamers in esters are higher under both polarities compared to that in MO [25, 35].

2.3.6 STREAMER ACCELERATING VOLTAGE

The accelerating voltage of the streamer is defined as the voltage at which the propagation velocity of a streamer increases more rapidly [30]. Notable variations exist in between the streamer propagation velocities of MO and the ester oils under positive polarity. The accelerating voltage is an influencing factor of streamer velocity in insulating liquids as discussed in the previous section. Below the accelerating voltage, the streamer velocity of MO and both the esters (NE & SE) increases marginally. However, just above the accelerating voltage, ester velocities increase more rapidly with increasing applied voltage when compared to the mineral oils. Under the negative polarity, the difference in streamer velocities and the velocity ranges of MO and esters is comparatively negligible. The observations reveal that the streamer propagation in ester liquids is still rapid with higher velocities than that of the streamers in MO. Although, both the streamers in MO and Esters starts propagating rapidly when the voltage is above the accelerating voltage, the velocities under positive polarity is comparatively higher (step and lightning impulse) [25, 33].

2.3.7 STREAMER SHAPE

The streamer shapes are mainly categorized into two types on the base of the voltage polarity, streamer velocity, and the structure of the streamer they form. They are “slow and bushy” and “fast filamentary”. As discussed in the above sections, generally the streamers generating from the negative needle are bushy in shape. Whereas, the streamers generating from the positive needle are in a shape of a leafless tree-top (filamentary) [25, 38, 43]. The generation of fast filamentary streamers mostly depends on the nature of the liquid, additives, or the applied electric field or hydrostatic pressure. According to many researchers [11, 22, 45, 46], the increase in any one of the above parameters gives rise to a fast-filamentary streamer shapes from a negative needle. Apart from the final lengths and propagation velocities, the features which comprises several branches along with the branch width aids in differentiating the streamer modes in both polarities of mineral oil and esters. Even though the stopping lengths of the streamers in MO and ester liquids are slightly comparable, their streamer shapes differentiate evidently. In [25], the author reports that the streamers in MO have one or two primary branches with numerous secondary branches, while esters seemed to have numerous primary branches travelling in various directions.

2.4 INFLUENCING FACTORS OF STREAMERS

As per the literature survey, it is understood that the parameters that influence the streamer characteristics are mainly the chemical composition (type of the liquid, purity, and additives), electrode geometry (gap, radius of the point or needle electrode) and electric field type (input voltage, magnitude, and polarity) [11-43]. Many investigations were carried out with the help of the latest optical technologies to visualize the pre-breakdown events in esters [44].

2.4.1 CHEMICAL COMPOSITION OF FLUID

The chemical composition of insulating liquid shows a significant effect on the propagation characteristics of the streamer. Electron affinity is the major affecting attribute due to the reason that a peripheral change in molecular structure of the liquids leads to major variation in the streamer velocity with respect to the voltage polarities [11]. It was reported that the existence of a single atom of chlorine in chlorocyclohexane caused substantial increase in velocity of the negative streamer, which was 10 times higher than that of actual cyclohexane [22, 43].

As reviewed in the earlier paragraphs, the positive needle tends to initiate a fast-filamentary streamer in chlorocyclohexane when compared to actual cyclohexane. This determines that the liquid's chemical composition impose an effect on streamer propagation characteristics. Normally, in most saturated hydrocarbon liquids, the negative needle with tip radii more than 10 μm tends to generate a bush–shaped streamer. Nevertheless, there is a chance that a negative streamer can be a tree-shaped in pure aromatic type of liquids [11]. However, changes in the viscosity of the liquid could not induce any considerable variations in streamer propagation characteristics [45].

2.4.2 EFFECT OF ELECTRODE GEOMETRY

The propagation modes and the velocity of the streamer in insulating liquids are highly dependent on the magnitude of the electric field. Recall that the electric field is controllable by the attributes of applied voltage, electrode geometry that includes tip radii and the inter-electrode distance and the injection and the ejection of the space charges in the oil. Electric field at the needle tip is the main attribute in initiating the streamers. This value decides the structure of the streamer initiation in the insulating liquids. Another parameter, the radius of curvature of the needle tip introduces a large electric field under moderate applied voltage when the tip radius is adequately small and vice versa. The streamer shape changes with changes in the needle tip radius. Smaller tip radii change the negative streamer structure from spherical to bush-like with increase in applied voltage.

Effect of gap length: For smaller inter-electrode gap length s, the electric field intensity at the tip of the needle will be high which aids in the initiation of the streamer for moderate values of the applied voltage. These results in smaller partial discharge inception voltages and it is to be understood that the streamer propagation velocity increases with increasing in applied voltage at smaller electrode gaps, which in turn increases the probability of breakdown to occur. While, the increase in gap distances causes the decrease in the electric field intensity at the needle tip, the PDIV, the streamer propagation velocity, the breakdown voltages thus decrease the probability of breakdown to occur. Here, the breakdown probability is defined as the number of breakdowns per twenty discharges at individual level of applied voltage [15]. The breakdown probabilities are higher in esters when compared to that in mineral oils [44]. Importantly, the time taken to breakdown is directly proportional to the electrode gap length whereas, the magnitude, time, number of partial discharges and the streamer length are inversely proportional to the gap length of the electrode [11, 43].

2.4.3 HYDROSTATIC PRESSURE AND TEMPERATURE

The pressure shows a notable impact on the streamer propagation characteristics. With minor increase in pressure, the shape and final length of the streamer get decreasing which furtherly form a string of globules. It is to be known that high adequate amount of pressure may vanish the streamer totally. As the voltage applied to the needle electrode and the pressure are directly proportional, high amount of pressure is required to clear the streamer initiated with higher value of the voltage. However, there is a negligible impact of pressure on streamer velocity [22]. It was understood from the report that the pressure above the threshold value that turns on with the streamer energy causes the streamer, streamer current and equivalent light pulses to disappear [11, 43, 45, 47]. For larger magnitudes and a greater number of current pulses, higher hydrostatic pressure is required to suppress or disperse the current pulses [45]. This concludes that the higher the pressure the higher the electrical breakdown strength is.

According to the literature, it is to be assumed that there were no concrete reports quoting any significant effect of temperature on the streamer propagation. This is because the physicochemical properties of the dielectric liquid changes accordingly with time. Any increase in the temperature causes the increase in the current pulses of slow-bushy streamers and at the same time shows no effect on fast filamentary ones. It is also known that temperature has no influence on the streamers at atmospheric pressure [11, 43].

As per the literature survey, it is understood that the parameters that influence the streamer characteristics are mainly the chemical composition (type of liquid, purity, and additives), the electrode geometry (gap, radius of the point or needle electrode) and the electric field type (input voltage, magnitude, and polarity). Many investigations were carried out with the help of the latest optical technologies to visualize the pre-breakdown events in esters. As discussed, there is a vast scope to examine in the pre-breakdown characteristics on behalf of several attributes; these show a significant impact on pre-breakdown events. Further, it is important to improve the comprehension knowledge of the streamer characteristics for enhancing the condition monitoring analysis of power transformer liquid insulation.

2.5 SUMMARY

In this chapter, a comprehensive review of the existing literature on the topic “prebreakdown and breakdown phenomena in ester liquids” has been reported. To understand and report fundamental knowledge on the present topic, citation concerning the background knowledge has been also included. The contents of this chapter were focused on the breakdown theories and significant streamer properties. In addition, the factors influencing the initiation and propagation of the streamer in the liquid dielectric medium were highlighted.

CHAPTER 3

EXPERIMENTAL METHODS AND MATERIALS

3.1 INTRODUCTION

In the present work, emphasis is laid on the pre-breakdown phenomenon of low pour point ester dielectric fluids. For comparative analysis, mineral oil has been also included. To understand the workability of low pour point liquids, breakdown measurements have been performed at different aging durations with different electrode tips. The thermal aging is performed at elevated temperatures in presence of Kraft paper and cooper for 6 weeks with an aging assessment at every 2 weeks. It is to be mentioned that point plane electrode setup with smaller electrode tip radii have been considered for the present research. This is because point–plane arrangement constitutes one of the basic configurations in the investigation of non-uniform electric fields and insulation properties in high voltage studies. Streamers onset and breakdown are easily monitored using this arrangement [48]. The characteristic properties of the streamer including, partial discharge inception voltage, breakdown-streamer inception voltage (BSIV), inception electric field (E), and breakdown voltage (BDV) have been reported for various liquids at different aging conditions for three different electrode tip radii. The thermal degradation of the liquids has been monitored by UV spectroscopy, turbidity, particle count, and acidity measurements as per ASTM/IEC methods. The present chapter describes the experimental procedure and materials adopted for the present research. The details of the pre-treatment process for the specimen samples, thermal aging, electrical testing setup, and physicochemical testing have been presented.

3.2 SAMPLE PREPARATION

In this work, three insulating liquids: mineral oil (MO) and two synthetic esters (SE1 and SE2) having a pour point less than -50°C have been adopted. The details of the insulating liquids selected for the present study are summarized in Table 1. It is to be mentioned that the values of liquid properties summarized below are provided by the manufacturer.

Table 1: Properties of the liquids tested.

Property	Standard	MO	SE1	SE2
Density at 20°C, kg/dm^3	ISO 3675	0.8672	0.915	0.95
Pour point (°C)	ISO 3016	-51	-75	<-65
Flash Point (°C)	ASTM D92	148	198 (ISO 2719)	248 (ISO 2719)
Fire Point (°C)	ASTM D2592	-	220 (ISO 2592)	284
Water content (mg/kg)	(IEC 60814)	9.2	21.1	29.8
Acidity (mgKOH/kg)	(IEC 62021)	<0.01	<0.03	0.01

The selected insulating liquids have been subjected to accelerate thermal aging with a controlled aging history. Later, the aged oil samples have been physicochemically and electrically characterized.

3.3 THERMAL AGING AND APPARATUS

3.3.1 AGING CELL ASSEMBLY

The assembly of the 304L grade stainless steel Spools from Kurt J. Lesker, Canada was used as thermal aging cells. The dimensional details and overview are presented in Figure 5. The ends of the spools are sealed with two stainless steel vacuum flanges using two copper gaskets and set of nuts and bolts (medium-strength Steel, Zinc-Plated from McMaster-Carr, USA). One end is fixed before filling the liquid, and the other end is sealed after filling the insulating liquid with a manual torque wrench. This allows a hermetic sealing during the accelerated thermal stressing of the liquid and avoids interactions with external air and moisture [49].

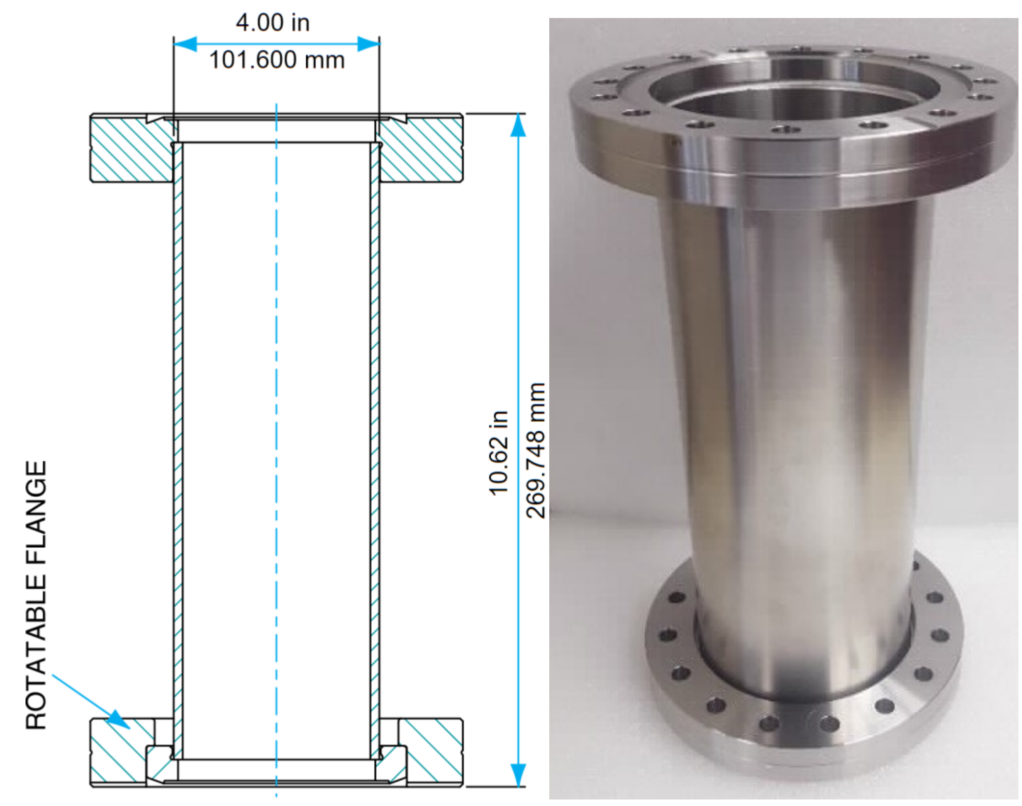


Figure: 5 The stainless-steel thermal aging cell © Jayasree Thota.

3.3.2 INSULATION PAPER: WEIGHTS AND ASSEMBLY

To replicate transformer materials, copper and insulating paper are introduced to the aging cells. In this work, the thermally upgraded Kraft (TUK) paper Insuldur® paper with 2.6% nitrogen content has been adopted. This is because Insuldur® was reported to be effective in maintaining the stabilizing additives in the insulating paper during the accelerated aging [50, 51]. The TUK paper from WICOR group have been sized to 200 mm x 25.4 mm (1 inch) strips using the twin-blade cutter from TMI. This led to having the weight of each TUK paper strip to 0.30 g approximately. A copper sample holding the paper strips has been developed according to reference [49]. Later, the paper strips have been hosted in the copper holder that allowed a free flow of liquid through the paper strips. The view of the paper sample holder and the assembly are presented in Figure 6. It is to be mentioned that each sample holder is prepared to host 13 strips of TUK papers.

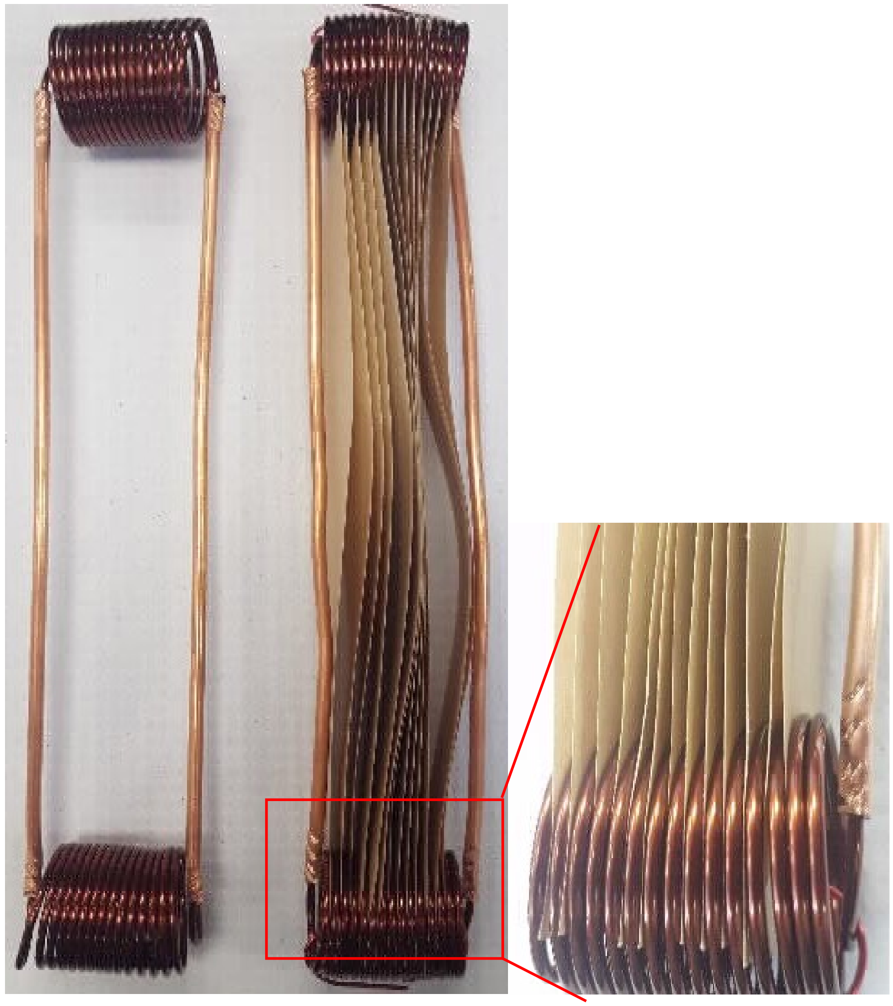


Figure: 6 View of copper holder and paper hosting assembly © Jayasree Thota.

In total, 9 aging cells have been prepared respectively for 2 weeks, 4 weeks, and 6 weeks aging of three insulating liquids. For this study, 1500 ml of liquid in each cell is planned for thermal aging while allowing the rest, 690 ml for the neck head space. This space would room the paper-copper assembly and also liquid volume raised due to thermal expansion during thermal aging. With respect to the densities of the proposed liquids, the weight of the oil samples and the weight of the paper with a ratio of 1:365 (paper: oil) are calculated and summarized in the table below.

Table 2: Mass distribution in aging cells

Characteristics	MO	SE1	SE2
Wt. of 1500 ml	1301 g	1373 g	1425 g
Number of paper strips	12	13	13
Wt. of paper (g)	3.56 g	3.76 g	3.90 g
Paper / liquid ratio	1: 365	1: 365	1: 365

3.3.3 PRE-TREATMENT AND THERMAL AGING

Before aging, the liquid samples and paper assembly underwent a preparation step to reduce the initial moisture content. The details of the individual treatment process are explained below.

Insulating papers: Nine paper-holder assemblies were placed in a vacuum oven for 48 hours at 80°C. Later, they were transferred to a portable dry storage desiccator cabinet (dry box) and stored for 18 hours before the dry box is opened in inert environment.

Insulating liquids: Insulating liquids were degassed for 48 hours in glass ampoules of 2000 ml volume. This is achieved by keeping the liquid-filled ampoules in a plastic vacuum desiccator situated on a magnetic plate stirrer. To provide a gentle and uniform stirring, magnetic stir bars are dropped into the liquid-filled glass ampoules. For effective absorption of moisture, a layer of silica gel balls has been introduced underneath and around the glass ampoule. Later, the degassed liquids were placed for 48 hours at 80°C in a vacuum oven for dehydration. While the preprocessing of the liquids is performed according to the acceptable scientific process, initial moisture measurements have not been performed. Later, the dry box (with paper-copper assembly) and the sealed dehydrated liquids were transferred to a double glove box for assembling the aging cells (liquids, paper-copper holders, and screwing the flanges) under dry nitrogen environment. This allows avoiding interaction with the environmental air and moisture during the long assembling process. Later, the complete tightening/screwing of the flanges was done outside the double glove box, as it was difficult to fix all the screws around the flanges inside the double glove box.

It is known that acid-catalyzed hydrolysis is the main and dominating degradation mechanism for cellulose decomposition as compared to that of the oxidation [52-54]. Therefore, to keep the minimal oxidation effect on the insulating paper degradation, inert environment is adopted in the present research. Thus, the aging of oil-paper insulation in the cells is facilitated to be governed mostly by the hydrolysis and temperature. In addition, open beaker aging will degrade the insulation to a higher extent (high decay content) than that is done by inert environment aging. Such a high degradation caused by accelerated aging process will tend to reduce the dielectric strength of liquids to a very low level and may include risk (high possibility of catching fire with large decay particles) while subjecting them to high AC stress with a small tip radius.

Later, the assembled aging cells were placed in a mechanical oven at 120°C for thermal aging. An aging cell/liquid is removed from the oven for every 2 weeks and is cooled down to room temperature around 22°C before collecting liquids for analytical purposes. All the cells were left unopened till the complete aging cycles are completed. For the last set of samples (six weeks), three days were left not attended. Later, all the cells were opened on the same day. The time after removing from the oven and opening the cells is different for 2 weeks, 4 weeks, and 6 weeks. But it is to be noted that this time (time to open) is same for individual aging groups which are used for comparative analysis (liquid-liquid at different aging groups). For instance, the time to open 2 weeks (MO, SE1, and SE2) is similar which will allow same equilibrium or partition of aging by products between the oil, the paper, and the open space in the aging cell. After opening the cells, each liquid is transferred into four different glass bottles (one 750 ml and three 200 ml) without having any neck head space and are stored in a dark chamber before characterizations. The volumes 750 and 200 ml are for physicochemical and electrical testing (3 needles) respectively. Similarly, the paper-copper assembly is sealed and stored in the dry box for future analysis. It is to be mentioned that before electrical testing no treatment is performed as the objective is to see the influence of the aging by-products on prebreakdown and breakdown behaviours.

3.4 PHYSICOCHEMICAL TESTING

To understand the degree of liquid degradation after accelerated thermal aging, physicochemical characterizations have been performed. The measurements include UV spectroscopy, particle count, turbidity and acidity characterizations. It is to be mentioned that the UV spectroscopy and particle counter apparatus were set to perform three measurements and compute the average value by the automated inbuilt graphical user interface. Turbidity and acidity measurements have been manually performed three times and the average of the three measurements are used for the analysis. To establish the baseline for the aged liquids, fresh unused liquids have been characterized.

3.4.1 ACIDITY

The measurement of the total acidity is a way to determine the liquid degradation during the service life of the transformer. The total acidity value should be low for a good insulating oil. The results (neutralization number) are reported in mg of KOH/g. In the present research, acidity measurements have been performed according to the standard ASTM D 1534 - 95 [55]. Acidity measurements are reported as a function of thermal aging to understand the level of liquid degradation.

3.4.2 PARTICLE COUNT

This test method uses optical particle counters to determine the particle concentration and particle size distribution in insulating oil. In the present research, the Pamas SBSS WG particle counter is adopted according to ASTM D6786 [56]. The apparatus scans the sample specimen and evaluates the details of the number of particles and size of the particle distribution. The details (count) on the number of particles ranging from 4 microns to 70 microns are obtained for each specimen. Even though, it is known that the number of particles increases with aging, condition monitoring engineers generally do not use a particle counter to determine the distribution of particles in the oil. The particle count testing is not the traditional practice of liquid evaluation in this field even if the standard exists. In this research, particle count measurements are reported as a function of thermal aging to understand the level of liquid degradation.

3.4.3 TURBIDITY

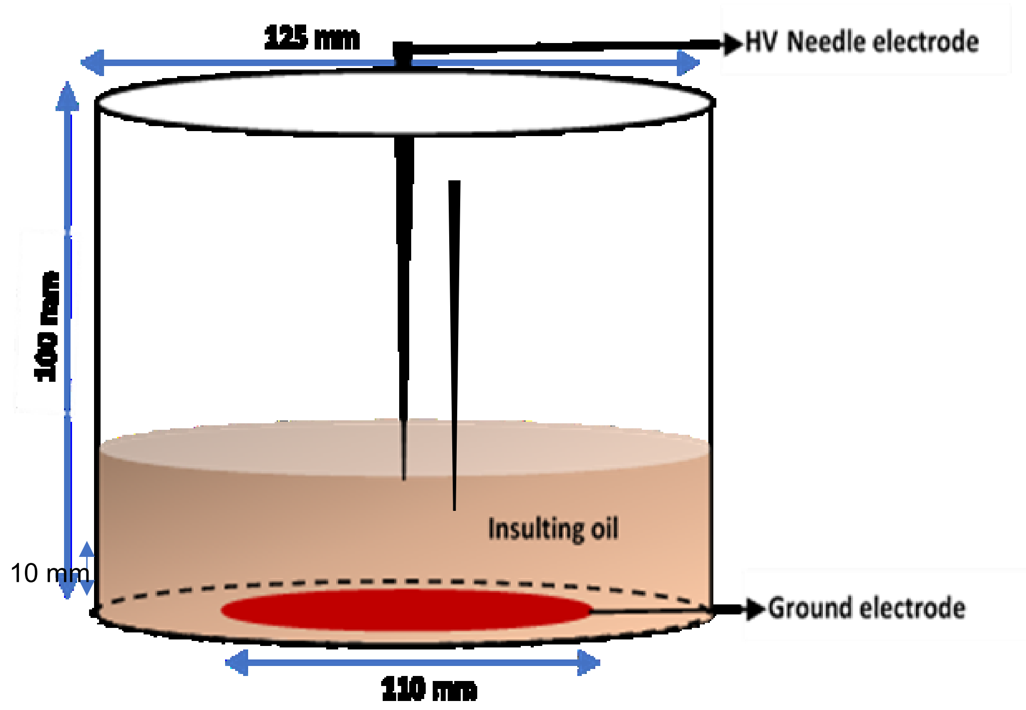
The Nephelometric measurement technique is a laboratory procedure used to determine a fluid's turbidity. This test is performed to observe the changes which may occur in the insulating oils. The results (value of turbidity) will be reported in Nephelometric Turbidity Units (NTU). This test method is performed according to the ASTM D6181 standard [57]. It is established that liquid degradation is accompanied by evolution of decay particles in the liquid, which influences the ability of the liquid to be transparent to light. Hence, in this research turbidity measurements are presented to understand the degradation of liquids.

3.4.4 DISSOLVED DECAY PRODUCT (DDP)

This test method uses a UV spectrophotometer to characterize the comparative level of dissolved decay products in mineral insulating oils of petroleum origin. It is to be understood that this analysis is not applicable for direct liquid to liquid comparison. Yet, it is used to understand the rate of degradation of ester liquids. In this method, specimen is scanned for absorbance to light in ultraviolet visible regions and a spectral curve is generated. The spectral curves are the absorbance of the specimen plotted against the wavelengths from 360 to 600 nm. The area under this curve is estimated as the relative concentration of dissolved decay products in the specimen. This test method is performed according to the standard ASTM D 6802 [58].

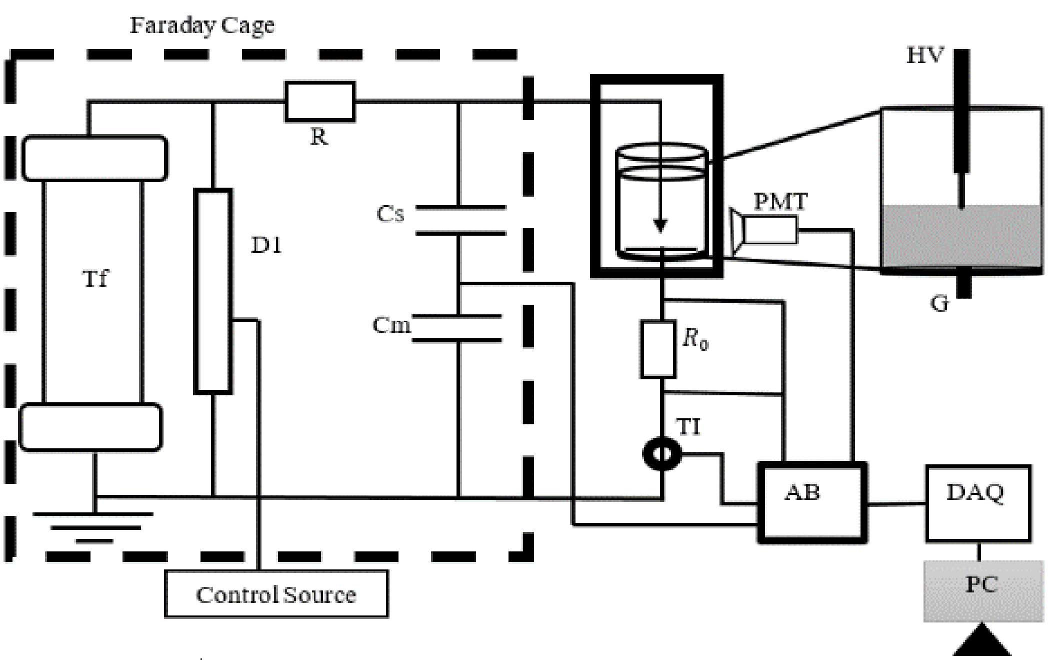
3.5 ELECTRICAL TESTING

To understand the prebreakdown and breakdown phenomena, fresh (unused) and aged oils have been subjected to breakdown under AC stress with a point-plane electrode configuration. Three convenient custom-made test cells have been developed with a point-plane electrode configuration, which is shown in the Figure 7a. The geometry of the test cell is as follows: diameter 125 mm, height 100 mm, and diameter/height of the plain copper ground electrode 110 mm / 1.5 mm. It is to be mentioned that 200 ml of liquid is used for testing in the cell between the high voltage and grounded electrodes.



(a) Schematic representation of the test cell © Jayasree Thota.

(b) Overview of experimental setup © Jayasree Thota.



(c) Illustration of electrical circuit

Figure: 7 Schematic and overview of experimental setup © Jayasree Thota.

Three tungsten high-voltage needle electrode tips of radius 0.93 μm (N1), 5.46 μm (N2), and 10.75 μm (N3) were used with an inter-electrode distance of 10 mm for three cells. As per the literature few works contributed to electrode tip radius less than or equal to 5 μm [59]. As per CIGRE brochure 157, most of the decay particles are less than 25 microns in diameter. As the present research aims to study the influence of aging, most of the decay particles in aged oils shall be less than 25 microns in diameter. Therefore, a smaller tip radius less than 25 microns of the radius has been adopted in this research. The schematic of the experimental setup is shown in Figure 7 (c).

A 100 kV, 5 kVA high-voltage transformer (Tf), is used as the source. The high-voltage needle electrode is subjected to the AC stress applied through the current limiting resistor (R). The capacitive divider (D1) aids in measuring the applied voltage through the control panel. The voltage applied across the electrode gap is increased at the rate of 1 kV/s until the breakdown occurs. It is to be mentioned that part of the applied voltage is rapidly applied, and later the controlled rate of 1 kV/s is maintained until the breakdown is achieved. The equivalent data of light emitted due to the ionization processes during pre-breakdown and breakdown phenomena are recorded with the photomultiplier tube (PMT) R928P from "Hamamatsu Photonics". The wavelength of the PMT ranges from 185 to 900 nm from ultraviolet to infrared, with maximum efficiency at a wavelength of 400 nm. The leakage current limiting resistance (R_0) connected in series to the test cell is set to 100 Ω [43]. A current transformer (T1) is connected between the R_0 and ground (G), this is used to record the leakage current. The corresponding source voltage, PMT signals, leakage currents, and breakdown voltages (in panel display) are recorded. This is achieved through a data acquisition system (AB, DAQ) connected to a computer (PC).

It is to be mentioned that each sample (fresh and aged liquids) is subjected to breakdown for five times with 4 minutes break between each measurement. All five individual results have been analyzed in MATLAB environment to obtain different characteristic parameters, and the average value is considered for analyses. The characteristic parameters include partial discharge inception voltage, breakdown streamer inception voltage, electric field stress, and breakdown voltage (BDV). It is to be understood that similar measurements have been performed with three different needle electrodes. This allowed observing the influence of tip radius while also emphasizing the influence of liquid’s degradation.

3.6 SUMMARY

In this chapter, the details of the materials and measurements have been presented. The base properties of the liquids adopted for the present research, the details of the paper-copper assembly, the aging cells, and the physiochemical measurements have been also described. The schematic of the experimental setup used for AC breakdown testing and the test cell with different needle electrode tip radii are also presented.

CHAPTER 4

RESULTS ANALYSES AND DISCUSSIONS

4.1 INTRODUCTION

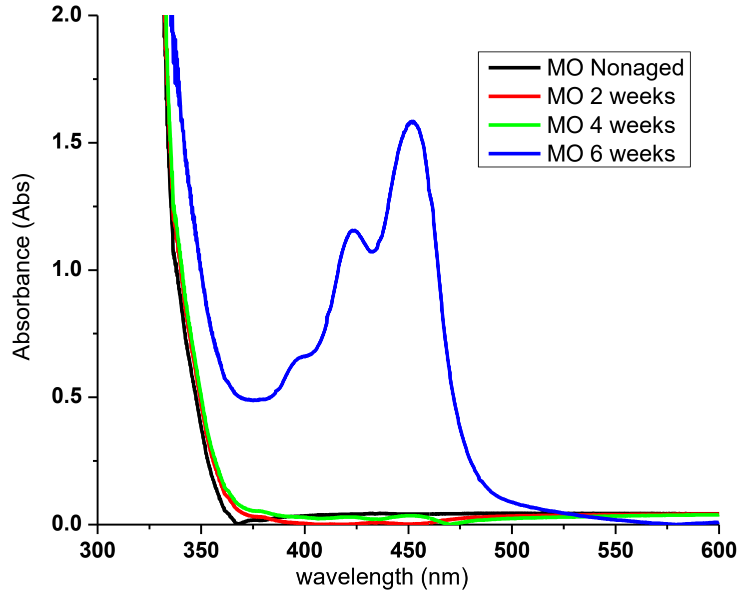
In the present research, some physicochemical and electrical testings have been performed. The details of the physicochemical testings include, turbidity, acidity, relative dissolved decay contents, and particle count. Electrical measurements include prebreakdown and breakdown measurements under AC stress at three different radii. The results of the study of the thermal degradation and electrical testing have been discussed in the following sections of this chapter.

4.2 PHYSICOCHEMICAL TESTINGS

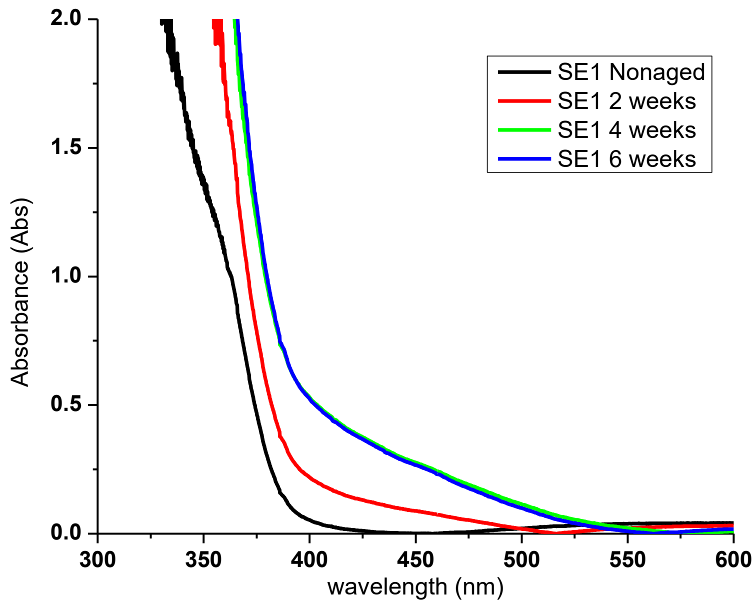
4.2.1 ULTRAVIOLET—VISIBLE (UV-Vis) SPECTROSCOPY

In the UV visible spectroscopy techniques, a beam of light from a UV visible light source passed through a transparent cuvette to establish a reference intensity. Later, the similar cuvette is filled with the specimen and is scanned again to record the absorbance of the sample. The difference in these intensities is used to understand the absorbance of the sample. The absorbance is found over a range of wavelengths to plot UV absorbance curves (absorbance vs wavelength). It is known that this absorption is dependent on the molar absorption and hence on the functional groups of the sample [60].

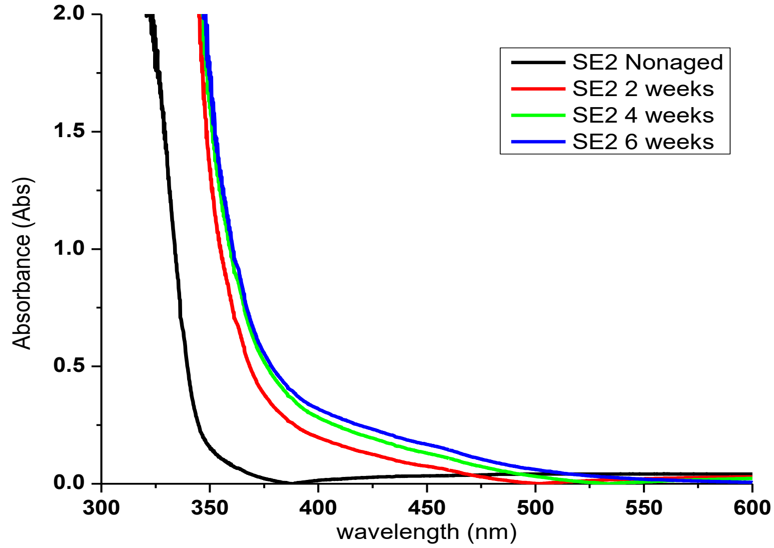
In transformer insulating oil, aging mechanisms introduce dissolved decay products (DDP) and the concentration of these decay products increases with degradation [61]. Thus, the absorbance of the liquid increases with degradation. This increase in absorbance with aging tends to shift the absorbance curve to higher wavelengths. Thus, there exists a relation between the area below the curve and the DDP in the liquid [61, 62]. In this work, UV visible spectroscopy measurements have been performed for mineral oil and ester liquids to understand the level of degradation. The absorbance of MO, SE1, and SE2 are reported at different aging factors (2 weeks, 4 weeks and 6 weeks) as shown in Figures 8 (a), 8 (b) and 8 (c).



(a) Mineral Oil (MO)



(b) Synthetic Ester 1 (SE1)



(c) Synthetic Ester 2 (SE2)

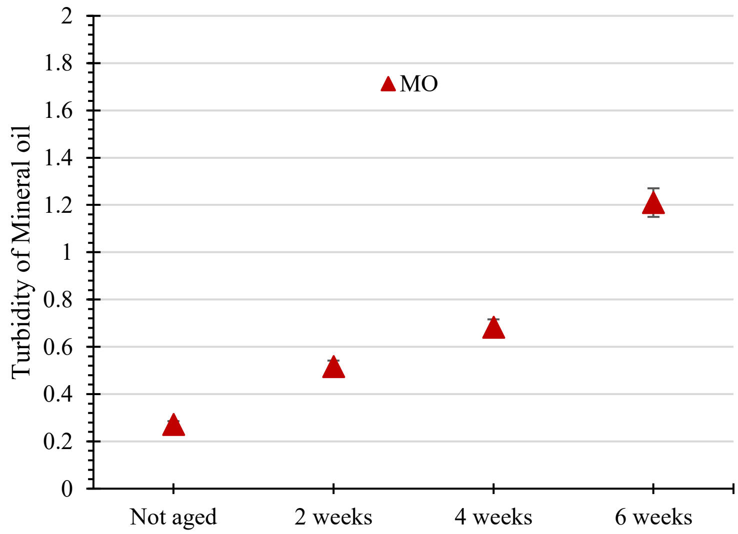
Figure: 8 The UV-Vis spectroscopy curves of insulating oils at different ages.

From the results of Figure 8, it is observed that the change in the absorbance and the equivalent change in the area between the curves increased with thermal degradation elapsed time. It is also noted that MO indicates a lower absorbance at early stages. However, with further increase in aging which means in the long run, the rate of rise in absorbance is large. The absorbance curves of SE1 and SE2 tend to increase in early aging conditions but starts to get stabilized with further increase in aging.

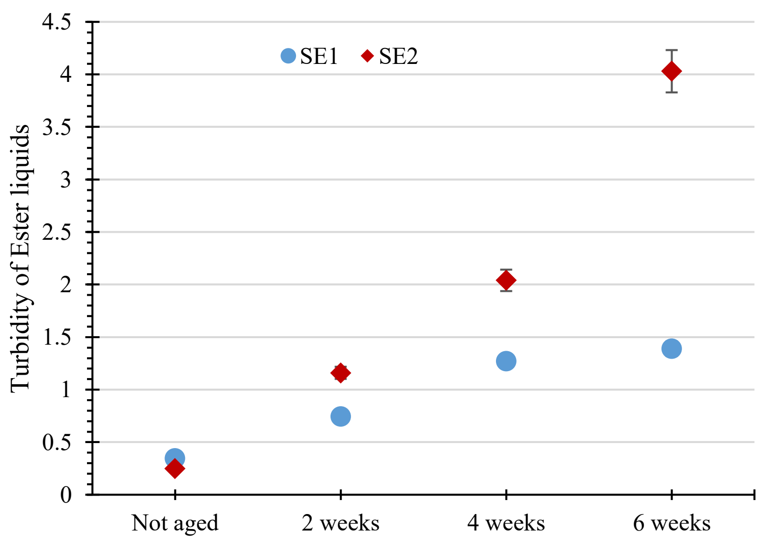
4.2.2 TURBIDITY

The thermal degradation of the oil/paper insulation is evident with the generation of colloidal and soluble decay contents to the bulk liquid. Therefore, the ability to transfer light through (turbidity) a transformer insulating liquid increases with increase in age. Therefore, this method provide an assessment of the insulation deterioration. The change in turbidity of non-aged and aged liquids

(MO, SE1 and SE2) at different aging conditions (2 weeks, 4 weeks, and 6 weeks) are as shown in Figure 9. As mentioned earlier, turbidity measurements are performed three times for each sample.



(a) MO



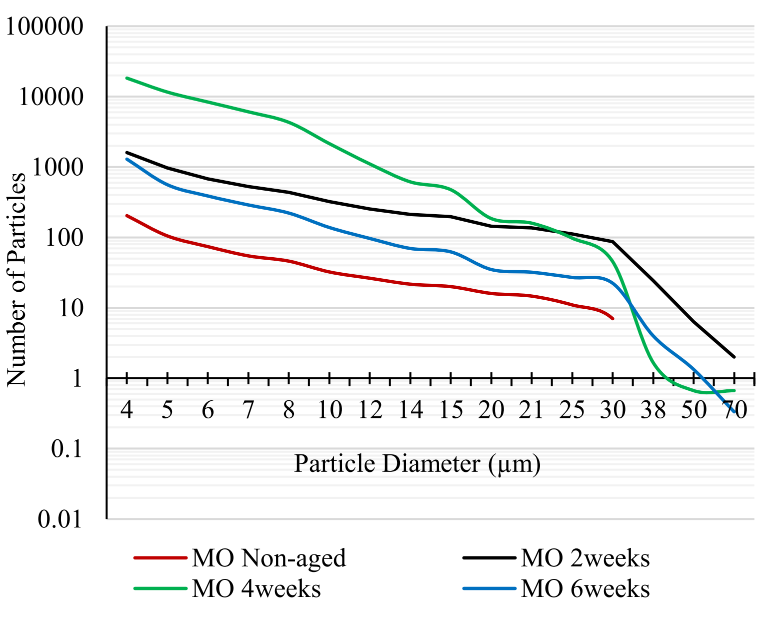
(b) SE1 and SE2

Figure: 9 Turbidity variation of MO, SE1, and SE2 with degradation.

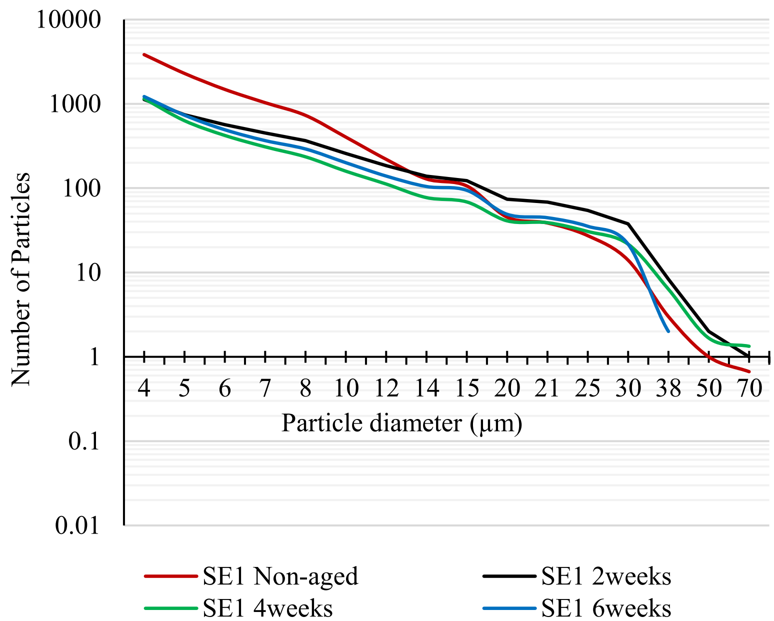
Due to different chemical compositions of the liquids, turbidity of mineral oil has been presented in a separate figure to avoid direct comparison. As expected, an increase in the turbidity of the liquids is noticed with thermal degradation. It is to be noticed that the rate of increase in turbidity of SE2 is higher as compared to that of the SE1 see Figure 9 (b). Which means the concentration of colloidal and soluble decay contents released in the liquid with thermal aging is higher in SE2 than in SE1. Hence, the increase in turbidity values of SE2 assesses that the rate of thermal degradation is lower in SE1 than that in SE2.

4.2.3 PARTICLE COUNT MEASUREMENTS

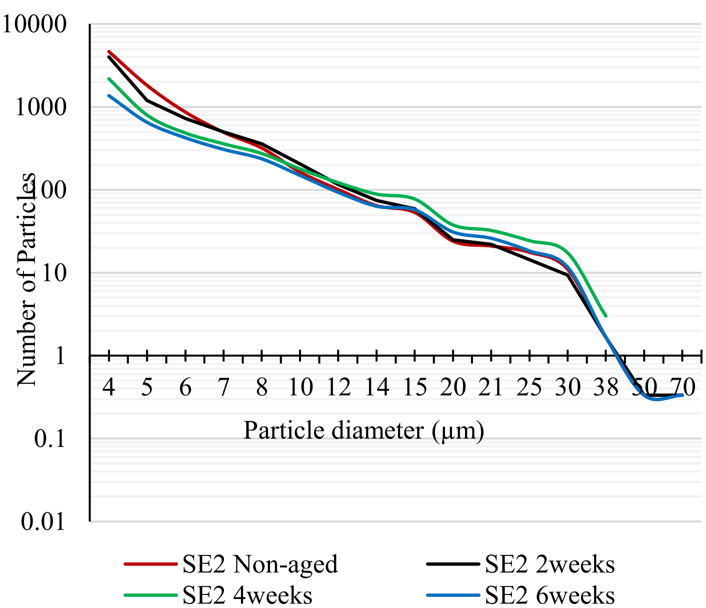
In addition to the above techniques, particle count measurements have been performed in order to assess the thermal degradation of insulating oils at different aging conditions. This measurement provided a quantitative information on the number of decay particles present in the liquid as a function of the particle diameter 4 - 70 µm. The graphical representation of the number of particles in various liquids with decay particle diameter at different aging condition is shown in Figure 10.



(a) Mineral oil



(b) Synthetic Ester (SE1)



(c) Synthetic Ester (SE2)

Figure: 10 Particle Count Measurement of MO, SE1 and SE2 at different ages.

In this work, the particle count measurements are measured as per ASTM D 6786 in cumulative mode of counting, thus resembling the descending nature of the curves for all the measurements. It is observed that the total number of particles in ester liquids are lesser as seen with that of the mineral oil. In case of SE1 and SE2, a significant change in particle trending is not seen with thermal degradation. A significant change is noticed in number of particles distribution with thermal aging in the case of mineral oil. It is to be understood that degradation of a liquid and decay particle size (diameter) may not follow a linear relationship with aging. This fact explains the non-uniform distribution of the decay particles size with aging. In addition, the inevitable agglomeration and division of particles with thermal excursions is also to be considered to further understand the distribution of the particles [63].

4.2.4 ACIDITY

The total acid number (TAN) is an established and widely accepted aging marker for mineral oils and ester liquids [64]. The oxidation by-products (peroxide gas, moisture, soluble acids, low molecular weight acids, fatty acids, alcohols, metallic soap, aldehydes, ketones, lacquers, sludge of asphaltene) usually result in an increase in acid number [65]. The acidity values of MO, SE1 and SE2 are measured as per ASTM D 974 and are plotted as a function of the aging duration as shown in Figure 11. As mentioned earlier, acidity measurements are performed three times for each sample and the average value is used for analytic purposes.

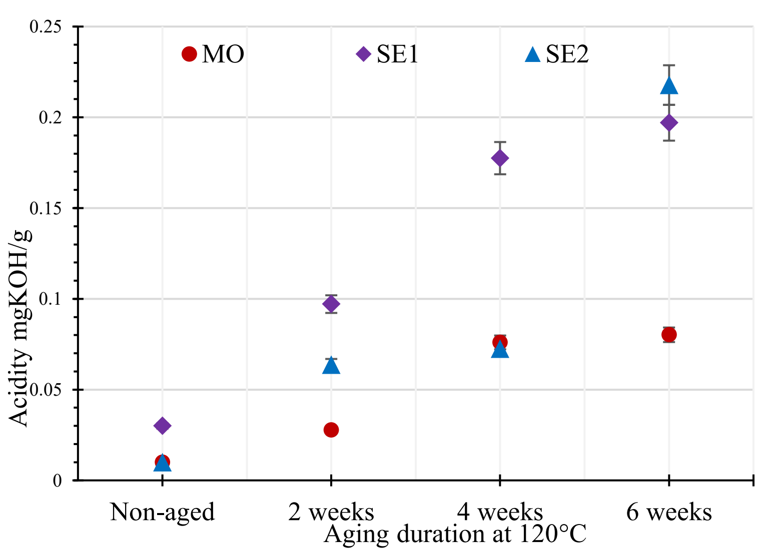


Figure: 11 Acidity of MO, SE1 and SE2 at different aging conditions.

It is noticed that the acidity values of both SE1 and SE2 tend to increase with increase in age while TAN values in MO is lower when compared. The reason behind the higher TAN values of SE1 and SE2 may be explained by the hydrophilic nature and acidic nature of ester groups. The high rate of hydrolysis in esters leads to the formation of acids in the ester insulating liquids [62, 64]. In addition, ester liquids are evolved from acid compounds, thus retaining a higher acid values than mineral oils [3, 4]. However, due to the high molecular weight and long-chain length of acids in ester groups, the detrimental level of the TAN in esters is significantly less as compared to that of the mineral oils. It is noticed that acidity of SE2 at 4 weeks is lesser than that of the MO at 4 weeks. This is theoretically not possible for similar aging condition. Therefore, considering this lesser acidity of SE2 at 4 weeks and tremendous increase at 6 weeks, it is clear that the trending is out of the normalcy. This may be attributable to the measurement error. Nevertheless, oxidation of esters leads to the formation of short-chain fatty acids, which promotes the development of the oxidation products [64]. The increase in acidity values for synthetic esters under air and nitrogen environments (due to hydrolytic degradation of esters) has been reported in [49, 66-68]. The acidity values obtained in the present research are higher than the ones reported in the existing literature. This may be due to the presence of large neck head space in the aging cell. There is a possibility for the air to enter the cells during tightening the flanges outside the double glove box. This will aid the oxidation and hydrolysis mechanisms in the cell during thermal aging. This high acidity values may also be attributable to the difference in the equilibrium/partition times considered for different aging groups (2 weeks, 4 weeks, and 6 weeks).

4.3 PREBREAKDOWN AND BREAKDOWN ANALYSIS

4.3.1 PARTIAL DISCHARGE INCEPTION VOLTAGE (PDIV)

The Partial discharge inception voltage (PDIV) is defined as the voltage at which the initiation of the streamers takes place. It is to be recalled that “streamers” [14] initiate the prebreakdown events followed by propagation prior to a complete breakdown in liquid gaps.

Therefore, the threshold value of the voltage at which the onset of discharges is noticed is termed as partial discharge inception voltage (PDIV). The electrode geometry (tip radius and inter-electrode gap) has a significant impact on the PDIV in liquids [69-71]. However, electrode tip radius has more effect on PDIV than the inter-electrode gap on PDIV.

The PDIV for MO, SE1, and SE2 for tip radii of 0.93 μm (N1), 5.46 μm (N2), and 10.75 μm (N3) at different aging durations have been presented in Figures 10, 11 and 12. The PDIV increased with increase in electrode tip radii and this trending is similar in MO, SE1 and SE2. This is because, the electric field intensity for an applied voltage decreases with increase in tip radii. In other words, electric field intensity for a given voltage will be high at sharp edges, small radius elements, rough surfaces, and needlepoint thus, allowing the electrode with smaller tip radius to initiate ionization processes at moderate voltages. Further, it is noticed that the PDIV is reduced with thermal degradation (Figures 12, 13 and 14).

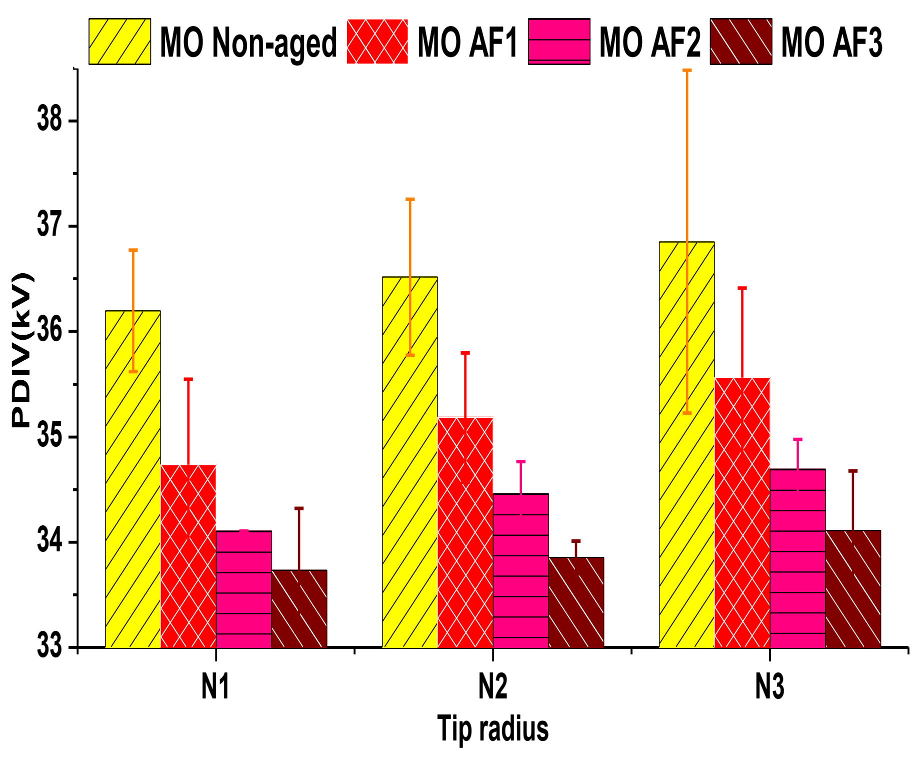


Figure: 12 Influence of the tip radius on the PDIV of MO with thermal aging.

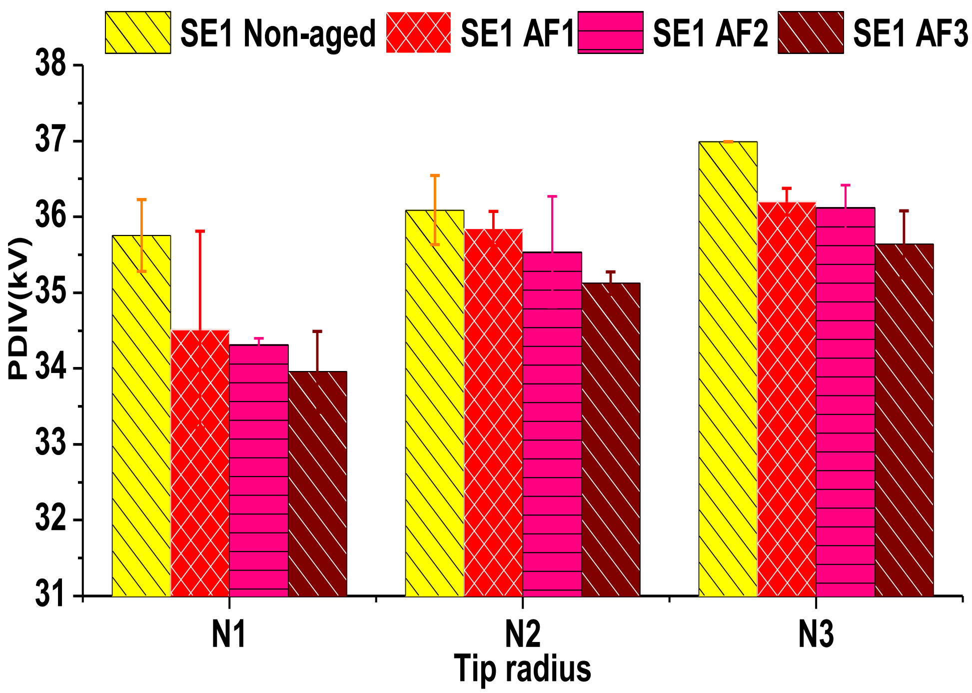


Figure: 13 Influence of the tip radius on the PDIV of SE1 with thermal aging.

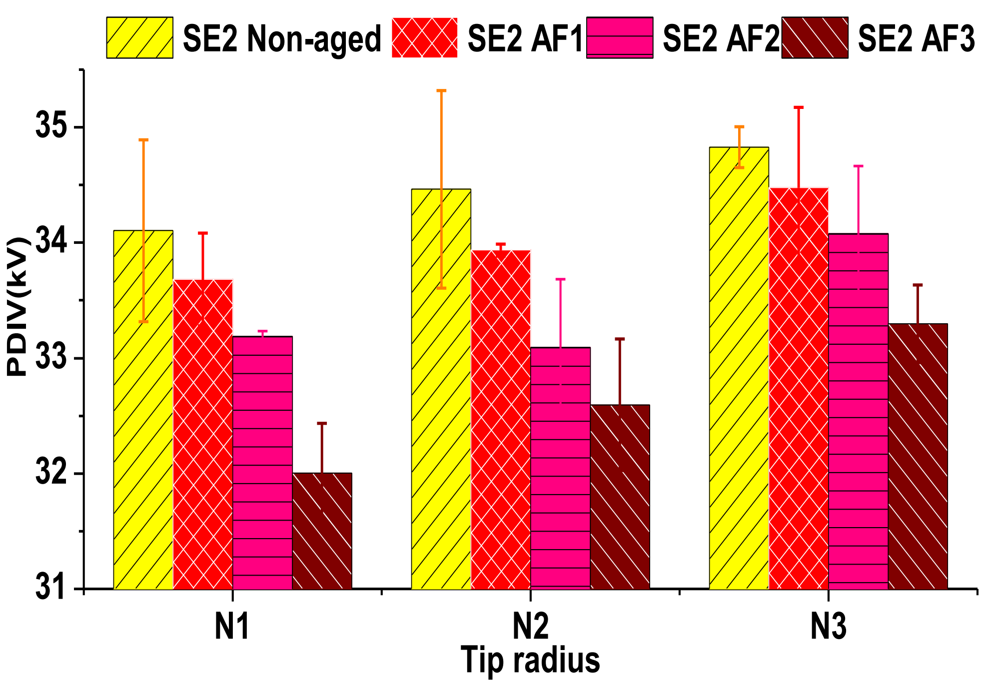


Figure: 14 Influence of the tip radius on the PDIV of SE2 with thermal aging.

This is because, aging introduces colloidal and soluble particles, which act as local conducting particles and aids in ionization. A combination of water and a dissociable substance increase conductivity [72]. Subsequently, initiation of streamers leading the prebreakdown processes is evident for relatively lower voltages. Considering liquid degradation and electrodes tip radius as influencing parameters, SE1 shows higher PDIV values when compared to that of SE2 and are comparable to MO.

4.3.2 BREAKDOWN STREAMER INCEPTION VOLTAGE

The breakdown streamer inception voltage (BSIV) is the voltage at which the streamer, which is responsible for the breakdown is initiated. According to streamer theories, a vapor bubble generated at the tip of the needle electrode when subjected to high voltage stress in a non-uniform field initiates a streamer. The continuous propagation of this initiated streamer in liquid medium until it bridges the inter-electrode gap is termed as breakdown. However, it is to be mentioned that not all the initiated streamers may propagate to result in breakdown. When the propagation of several streamers terminates in bulk volume of liquid prior to breakdown, this event is defined as partial discharges. The voltage at which the first streamers initiate is called PDIV. Aside from this, the streamers responsible for the breakdown is referred as breakdown streamers. The applied voltage at which the initiation of a breakdown-streamer is spotted may be termed as breakdown-streamer inception voltage. The BSIVs of SE1, SE2, and MO at different aging factors with N1, N2, and N3 are presented in Figures 15, 16 and 17.

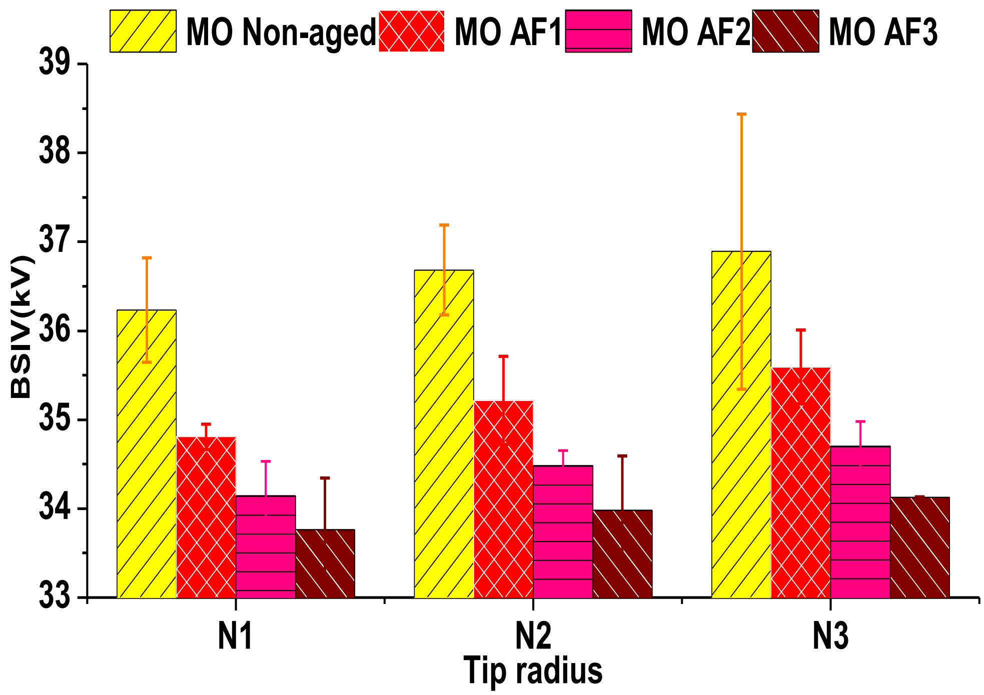


Figure: 15 Influence of the tip radius on BSIV of MO with thermal aging.

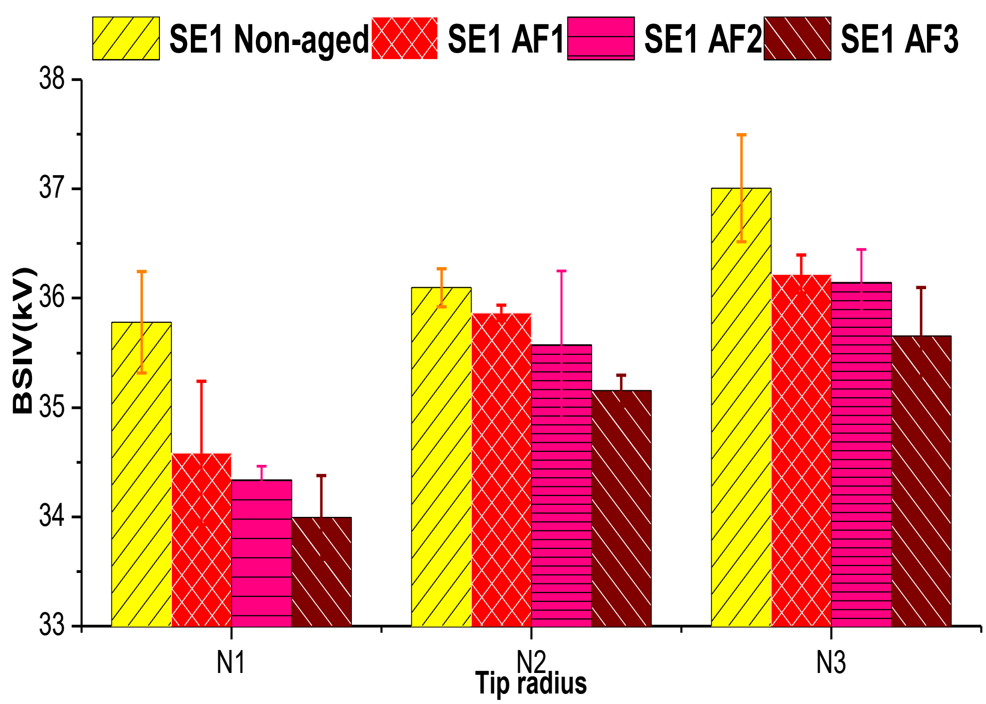


Figure: 16 Influence of the tip radius on BSIV of SE1 with thermal aging.

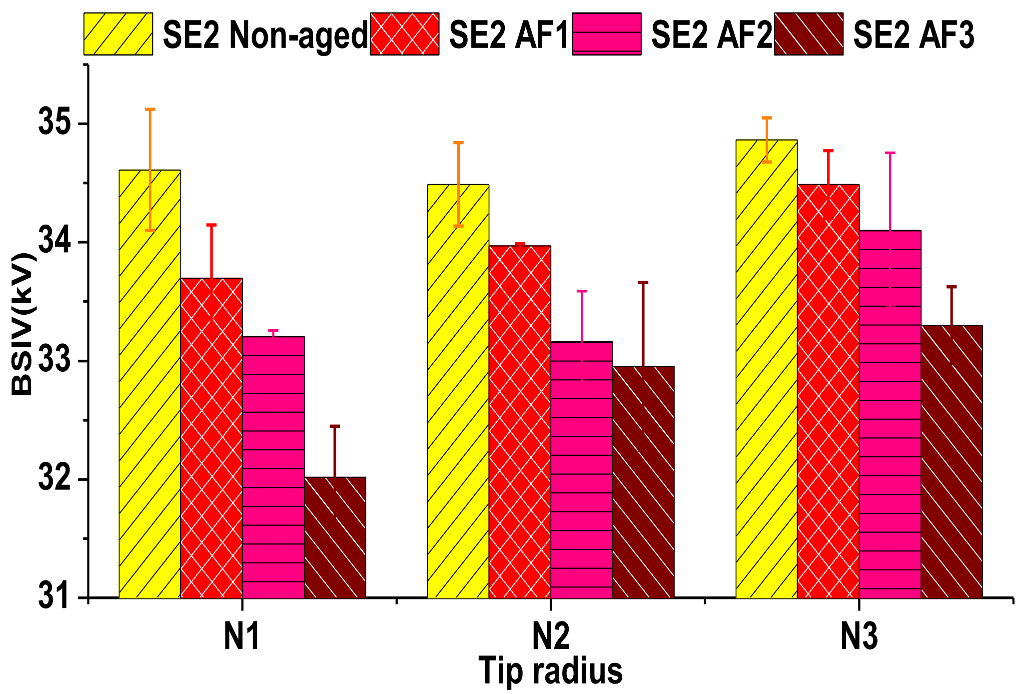


Figure: 17 Influence of the tip radius on BSIV of SE2 with thermal aging.

The BSIV increased with increase in the electrode tip radii and this trending is similar in all the liquids. In general, the propagation of streamers depends on the applied voltage and hence on the field intensity at the time of streamer inception. The electric field intensity (E) values corresponding to the BSIVs of all the samples (non-aged and aged) for all tip radii (r) and inter electrode distance (d) have been computed using COMSOL Multiphysics 5.6 interface.

The electric field intensities corresponding to BSIV for all the samples at different tip radii are illustrated in Figure 18.

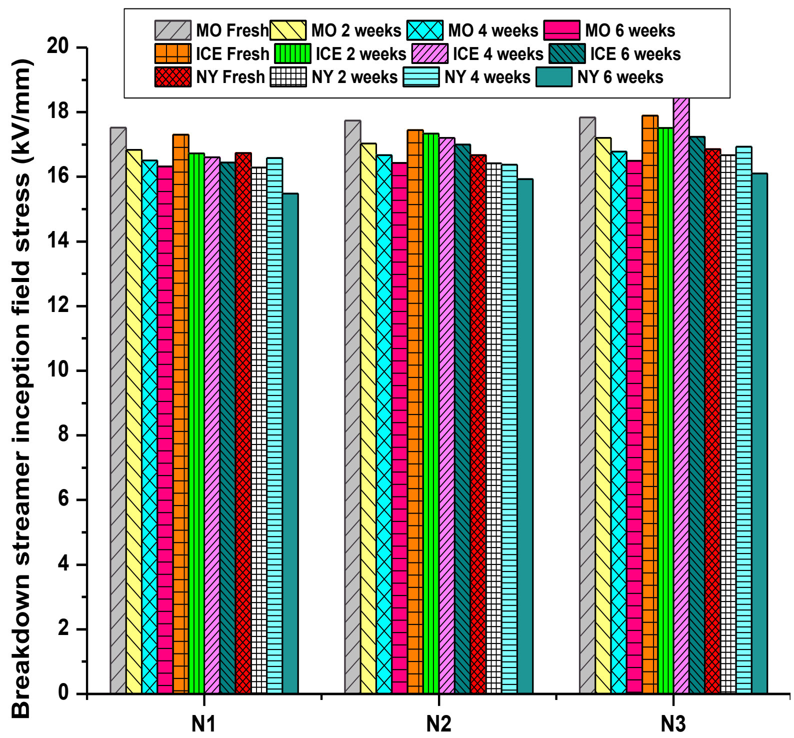


Figure: 18 Electric field stress of the tip radius at BSIV for different ages.

It is to be observed that the values of inception electric field stress at BSIV tends to decrease with increase in the thermal degradation duration of the liquid samples. From Fig.12, it may be noticed that liquid degradation has a noticeable significance on initiating the streamers leading to breakdown at a relatively lower inception electric field. Considering the influence of tip radii and the thermal degradation, SE1 shows higher BSIV than that of SE2.

4.3.3 BREAKDOWN VOLTAGE (BDV)

The breakdown voltage measurement is a significant way of defining the value of voltage up to which an insulating material will withstand the voltage stress. The BDVs of MO, SE1, and SE2 at different aging conditions for three different needle tip radii have been measured and reported in the Figures 19, 20 and 21.

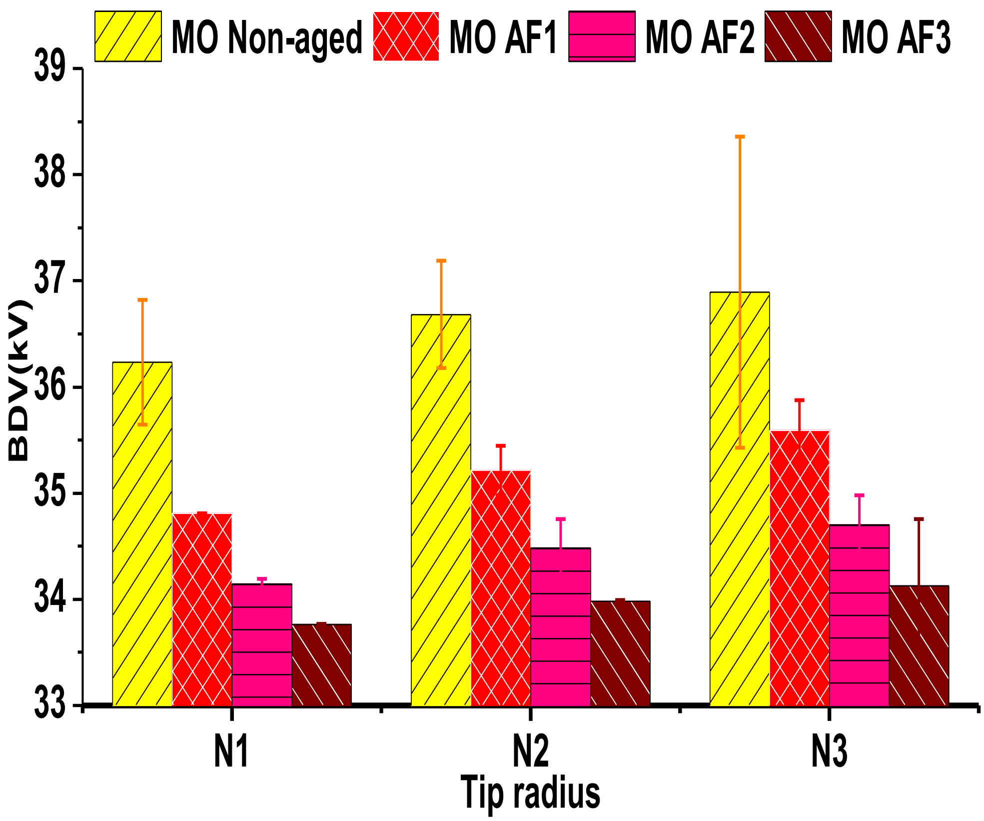


Figure: 19 Influence of the tip radius on the BDV of MO with thermal aging.

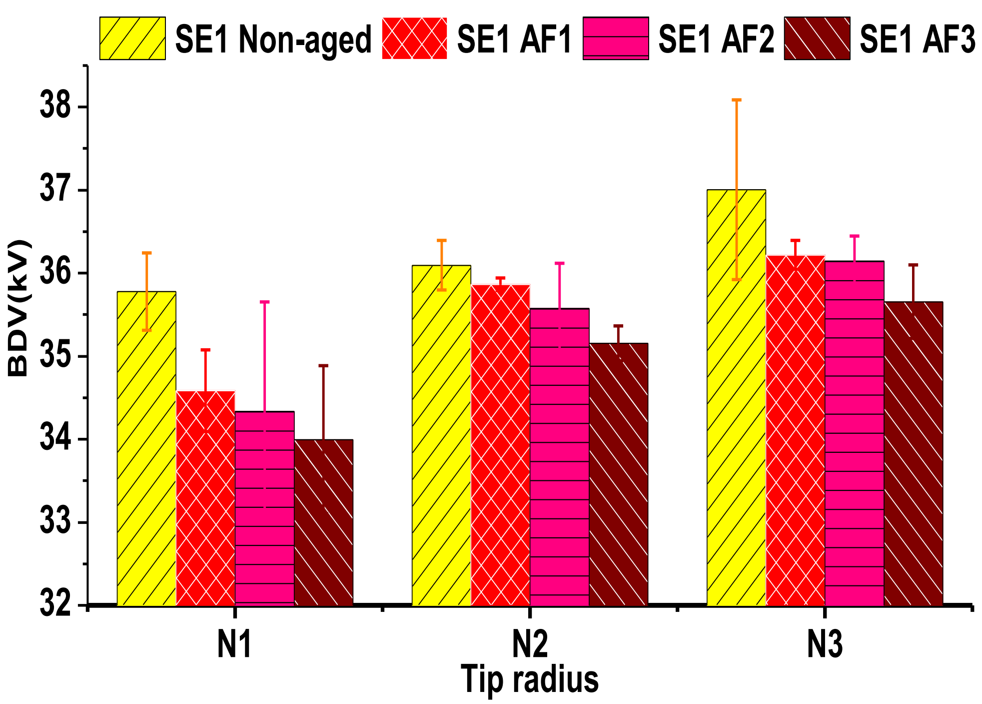


Figure: 20 Influence of the tip radius on the BDV of SE1 with thermal aging.

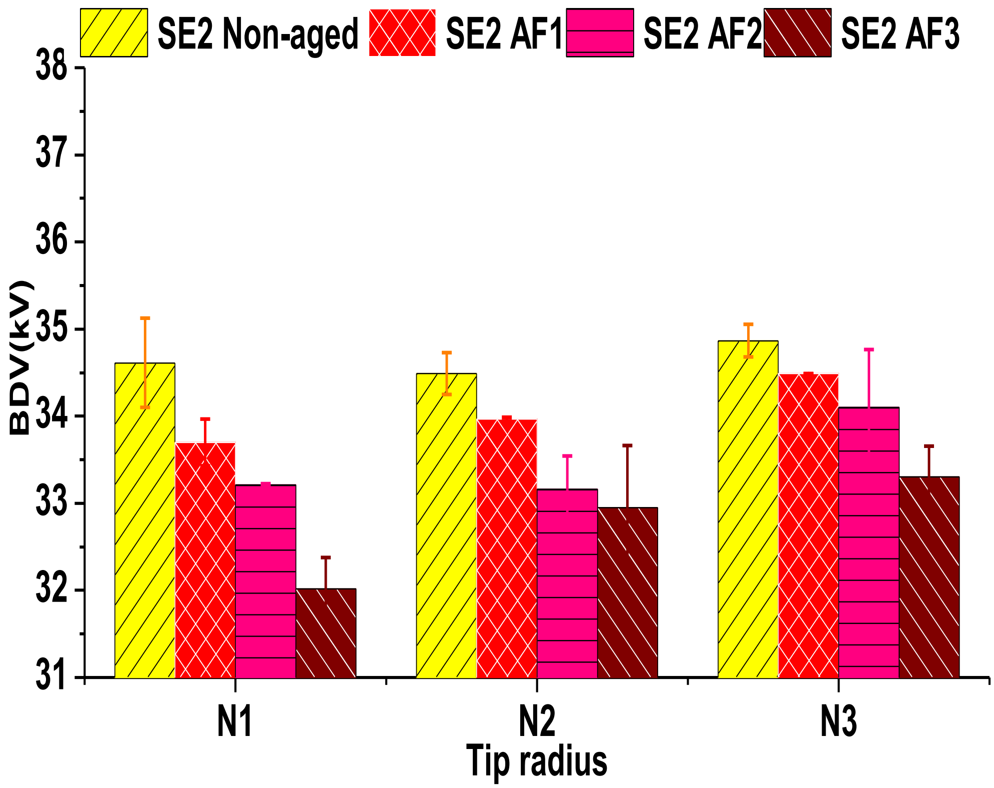
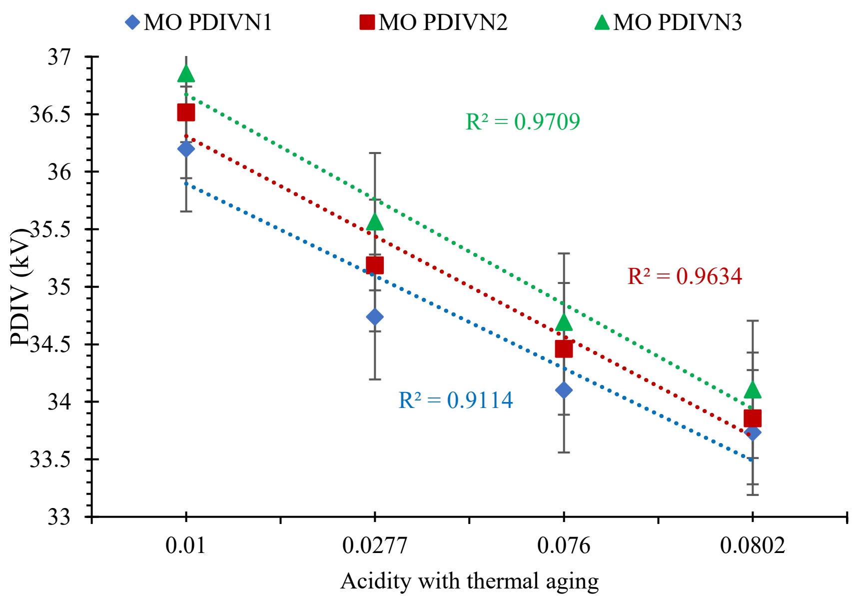


Figure: 21 Influence of the tip radius on the BDV of SE2 with thermal aging.

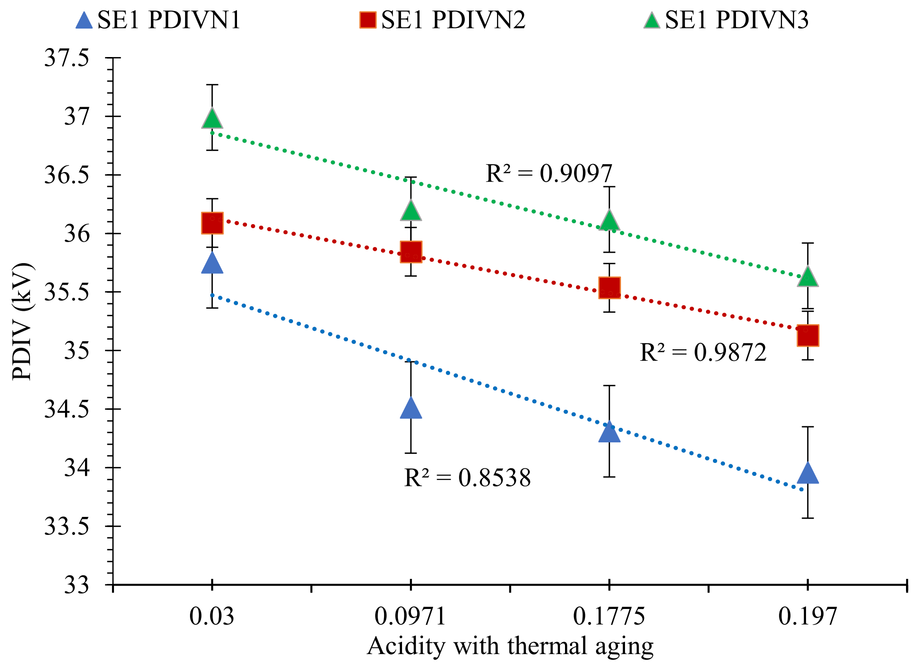
The BDVs of almost all the samples tends to increase with increase in needle electrode tip radii. This is because, field stress `will be low at larger electrode tips and vice-versa. Considering the degradation of liquids, the BDV values decrease with increase in liquid deterioration. For the present experimental condition, the BDVs of SE1 are better than SE2. In addition, the breakdown voltages of SE1 are comparable to that of the MO. To further comment on breakdown voltages, breakdown failure rates may be looked for the said liquids. It is also noticed that the difference between BSIV and BDV is small. This is due to the smaller tips (sharper tips) and smaller inter electrode gap. As discussed above, each sample (fresh and aged liquids) is five times subjected to breakdown with 4 minutes break between each measurement. The average values of the processed data are used for analysis in the above sections.

4.4 INFLUENCE OF THERMAL AGING ON PREBREAKDOWN PHENOMENON

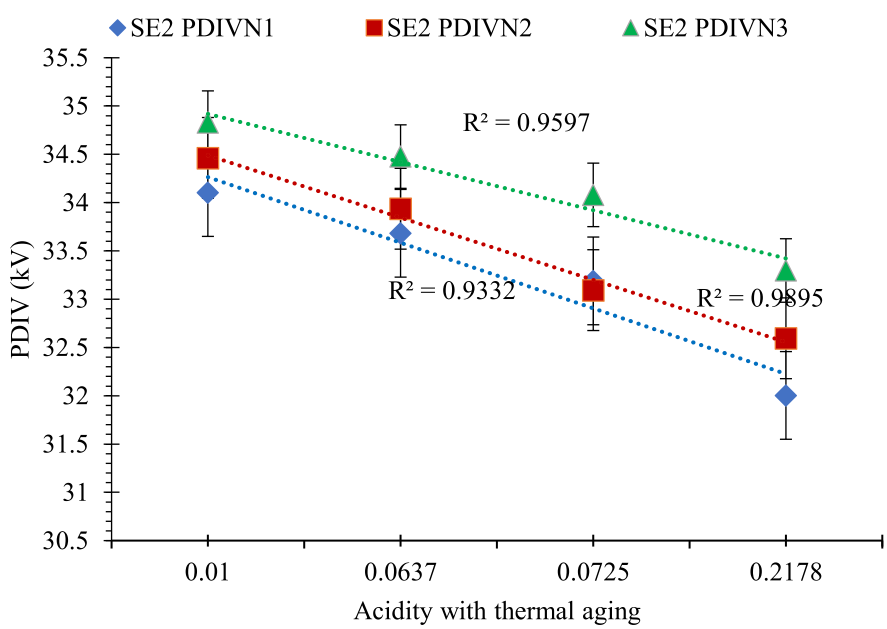
It is phenomenally known that the liquid degradation influences the prebreakdown and breakdown phenomena. Nevertheless, this influence has not yet quantitatively reported in the literature. Thus, in this section, two correlations have been reported to understand the affect of thermal degradation on the pre-breakdown phenomenon. The first correlation (FC) is established between the PDIV and acidity as the acidity is a widely accepted aging marker for both MO and ester dielectric fluids. The details are presented in Figure 22.



(a) Mineral oil



(b) Synthetic Ester (SE1)

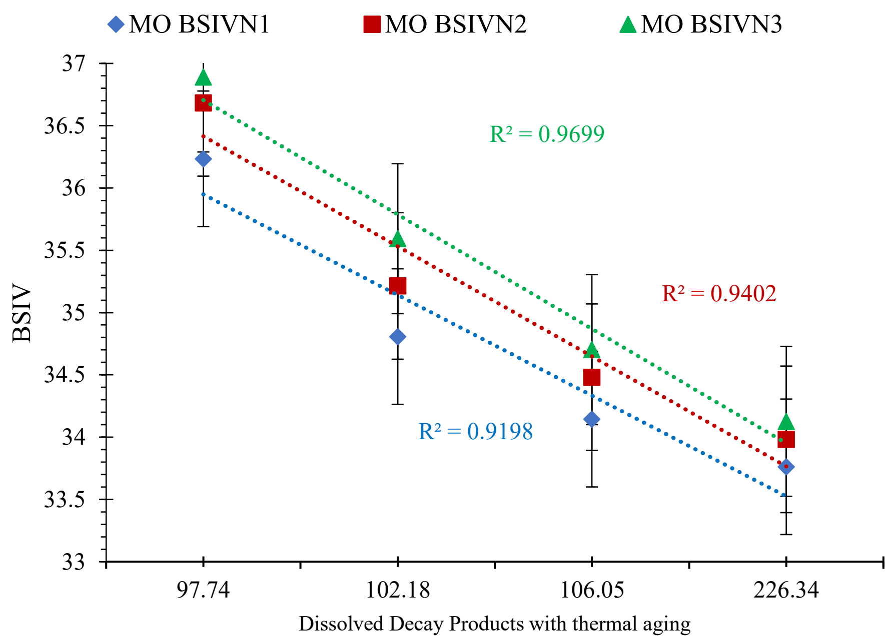


(c) Synthetic Ester (SE2)

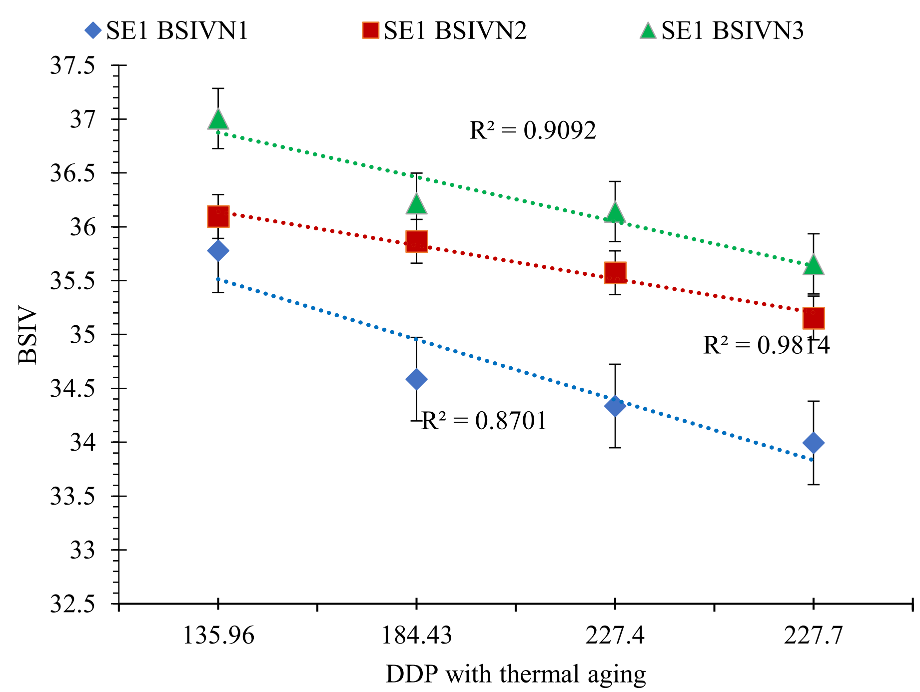
Figure: 22 Correlation between the PDIV and the acidity. The tip radius acted as parameter.

The objective of first correlation is to understand the influence of liquid’s degradation on PD onset. The acidity is a widely accepted aging marker for mineral and ester liquids, thus indicating a significant information on liquid degradation. The first correlation between PDIV and acidity indicates a potential relation between the liquid’s degradation and the onset of ionisation in the liquid volume. This correlation yields an almost linear correlation between PDIV and acidity regardless the needle tip. It is also understood that liquid’s acidity depicts a linear relationship with the onset of ionisation in the bulk liquid. This indicate that higher acidity of the liquid offers more chances for the onset of PD for lower applied voltages at any tip radius.

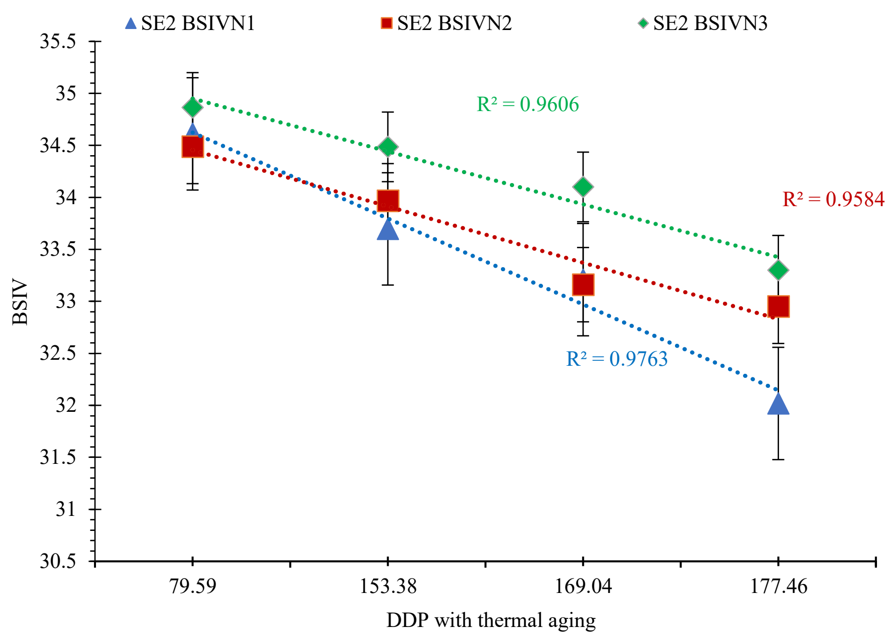
The second correlation (SC) is performed between the BSIV and the DDP. The details are as shown in Figure 23. The second correlation is intended to understand the influence of aging on streamers propagation. The liquid degradation introduces dissolved decay contents that may act as local conduction particles. Thus, aiding the ionisation in the bulk of liquid. Hence, the second correlation is performed between BSIV and DDP. It is understood that a strong relationship exists between the voltage that initiate the breakdown streamer and concentration of DDP in the liquid. It is also evident that the tip radius will not have any affect on the BSIV to yield a linear relationship with DDP. It is also learned that the increase in concentration of DDP aid the streamers propagation that may bridge the gap between the electrodes for lower applied voltages.



(a) Mineral oil



(b) Synthetic Ester (SE1)



(c) Synthetic Ester (SE2)

Figure: 23 Correlation between the BSIV and the DDP. The tip radius acted as parameter.

To demonstrate the association of the variables in the FC and SC, coefficients of determination (R-square) are listed. In addition, to understand the statistical significance, standard error is represented in Figures 20 and 21. It is to be noted that all the R-squared values are close to 1 (≈0.9) and the P-values are less than 0.05. Hence, it is revealed that PDIV and BSIV may be correlated with TAN and DDP under the selected experimental conditions. However, FC and SC may be understood with additional experimental data (or extrapolated) to develop pertinent transformer diagnosis/prognosis methods.

4.5 SUMMARY

In this chapter, the results of the prebreakdown and breakdown analysis have been presented. The analysis aimed at understanding the influence of liquid's degradation and influence of high voltage needle electrode tip radius on the prebreakdown and breakdown processes. The liquid's degradation have been monitored by suitable ASTM standard test methods and the related results have been also discussed. The influence of the thermal aging on the prebreakdown properties is reported by suitable correlations. Under these laboratory conditions, it is inferred that acidity and concentration of dissolved decay products are linearly associated with the partial discharge inception and streamer propagation.

CONCLUSION

In the present thesis, the pre-breakdown and breakdown phenomena of low pour point ester liquids have been experimentally investigated. The physicochemical testings have been performed at different aging factors while electrical measurements have been performed under AC stress at different tip radii in a point plane electrode configuration. It is to be mentioned that the electrical testings are performed for insulating liquids at different aging factors. The results and analysis of this thesis allow understanding the influence of thermal degradation on the pre-breakdown and breakdown processes. As the electrical measurements are performed with three different needles, this reveals the influence of tip radii on the behavior of the streamer characteristics at different aging factors. Investigating the influence of the thermal aging on the breakdown behaviour of low pour point ester liquids are one of the main aspects where the present thesis contributes. Recall that, the influence of tip radius on the breakdown behaviour of typical ester liquids is reported in the literature. The same (influence of tip radius) is verified for low pour point ester liquids.

The observations from the present thesis are summarized in details below:

Influence of thermal aging: It is to be known that the life span of oil filled power transformer is controlled by the degradation level of the oil/paper insulation system. This aging process results in formation of sludge, water, acids and colloidal suspensions, which are distributed in the liquid volume. These colloidal suspensions present in the liquid will acts as local conducting particles at high voltage stresses. This aids in easy and early ionization to further progress the streamer initiation and propagation behavior. Therefore, understanding the influence of thermal aging on prebreakdown phenomena is interesting and is reported in this thesis.

As highlighted above, in this research, three different low pour point liquids have been adopted, namely mineral oil (MO) and two different synthetic esters (SE1 and SE2). The fluids were subjected to thermal aging at 120°C for 2 weeks, 4 weeks, and 6 weeks and are tested subjected for testings. Additionally, fresh liquids are also considered for reference purposes. Therefore, this allowed highlighting the influence of liquid's degradation at different aging conditions on the streamer initiation and propagation parameters such as partial discharge inception voltage, breakdown-streamer inception voltage, breakdown voltage and inception field stress (E). It is observed that the values of the PDIV, the BSIV and the BDV decreased with increase in thermal degradation in all the liquids. It is observed that with aging elapsed, the SE1 depicted a better pre-breakdown and breakdown behavior when compared to the SE2. However, the prebreakdown and breakdown behavior of SE1 is comparable to that of the MO. To better understand the level of liquid's degradation, the physicochemical characterizations such as UV-Vis spectroscopy, turbidity, acidity, and particle count measurements have been reported. It is observed that concerning the liquids thermal degradation, the SE1 is better than that of the SE2 and MO.

Influence of tip radius: As per the literature, most of the research using this electrode configuration was carried out for the tip radius of more than 25 µm. Few works contributed to electrode tip radius less than or equal to 5 µm [26]. As per CIGRE technical brochure 157, most of the decay particles are lesser than 25 microns of diameter. As the present research aims at studying the influence of aging, the majority of the decay particles in aged oils shall be less than 25 microns of diameter. Therefore, a smaller tip radius lower than 25 microns have been adopted in this research. In order to demonstrate the effect of the tip radii on the prebreakdown and breakdown processes, non-aged (fresh) and thermally aged insulating liquids are subjected to AC stress with a needle-plane electrode configuration at 10 mm gap distance for three different needle tips radii: 0.93 µm (N1), 5.46 µm (N2), and 10.75 µm (N3). It is verified that the PDIV, BSIV, and BDV increased with the increase in electrode tip radii in the liquids. This is because, the electrode field intensity for an applied voltage decreases with increase in the tip radii. In other words, the electric field intensity for a given voltage will be higher at sharp edges, small radius elements, rough surfaces, and needlepoints, thus allowing the electrode with smaller tip radius to initiate ionization processes at moderate voltages. In terms of effect of the electrode tip radii on the prebreakdown and breakdown phenomena, the performance of SE1 is better when compared to that of SE2.

FUTURE SCOPE

This dissertation reports about the study of pre-breakdown and breakdown phenomena in ester fluids. However, there is a considerable scope to be further investigated as an extension to this work to see the possibilities of applying these low pour point ester fluids in the power transformers serving in cold climatic regions. Therefore, the pre-breakdown and breakdown tests of thermally aged ester fluids could be carried out at low temperatures in order to examine the temperature dependence on pre-breakdown behavior. This investigation may give proper idea regarding the dielectric performance of the ester fluids at very low temperatures.

Further aging studies may also be carried out to understand the appropriate aging markers and critical limits of ester fluids for diagnosis purposes. In addition, various regeneration avenues for ester fluids may be performed to investigate about the different adsorbents that works well for reclamation of esters as there is very limited literature regarding this perspective.

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