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ESTERS SYNTHÉTIQUES COMME ALTERNATIVES À L'HUILE MINÉRALE POUR TRANSFORMATEURS DESTINÉS AUX RÉGIONS FROIDES

Par Jayasree Thota

Sous la direction de Issouf Fofana, Stephan Brettschneider,

et Esperanza Mariela Rodriguez Celis

Thèse présentée à l'Université du Québec à Chicoutimi en vue de l'obtention du grade de Philosophiae Doctor (PhD) en ingénierie

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SYNTHETIC ESTERS AS ALTERNATIVES TO MINERAL OIL FOR TRANSFORMERS SERVING IN COLD REGIONS

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RÉSUMÉ

Les transformateurs de puissance sont parmis les équipements les plus critiques et les plus coûteux connectés à un réseau électrique. La durée de vie attendue d'un transformateur de puissance rempli de liquide est généralement de plusieurs décennies. Cette durée de vie dépend principalement des performances du système d'isolation huile-papier. La surveillance de l'état de santé, les diagnostics et la prévision de l'état du système d'isolation du transformateur sont donc d'une importance technique et économique considérable. C'est pourquoi les ingénieurs des utilités surveillent périodiquement ou en continu les systèmes d'isolation (huile/papier) afin d'assurer un fonctionnement sûr et efficace du transformateur. La surveillance de l'état de l'huile isolante du transformateur comprend généralement des tests de diagnostic, le reconditionnement et la régénération. Les tests de diagnostic (physicochimiques et électriques) sont réalisés conformément à des routines de surveillance de l'état du transformateur. Les activités de reconditionnement et de régénération dépendent généralement de l'état de dégradation de l'isolation, de la durée de vie utilisée/vie résiduelle, et des produits de dégradation présents dans l'huile. Les caractérisations physicochimiques sont réalisées pour évaluer l'état du système d'isolation. Malgré une surveillance périodique, la dégradation des systèmes d'isolation ne peut être arrêtée : les caractérisations physicochimiques permettent de suivre la dégradation de l'isolation et d'assurer un fonctionnement sûr grâce à des mesures préventives soigneusement sélectionnées. Les activités de reconditionnement et de régénération font partie des mesures préventives prises en fonction du niveau de dégradation de l'isolation. Ces traitements peuvent prolonger la durée de vie de l'isolation solide.

Au cours des dernières décennies, la demande pour une durabilité environnementale et une tout en supportant des de puissance électrique élevées , a augmenté à l'échelle mondiale. Ainsi, les liquides diélectriques à base d'ester sont considérés comme une alternative potentielle aux liquides isolants minéraux. Les liquides diélectriques à base d'ester sont réputés pour leur meilleure maniabilité et durabilité, avec une durée de vie améliorée des systèmes d'isolation solide. Cependant, l'application des esters continue de poser des défis aux propriétaires de transformateurs et aux ingénieurs des services publics, notamment dans les régions froides. Le comportement diélectrique et le profil de viscosité de ces nouveaux liquides à des températures extrêmement basses sont difficiles à gérer. D'un autre côté, le comportement en fin de vie de ces nouveaux liquides est également un sujet de préoccupation majeur pour les propriétaires de transformateurs.

L'objectif principal de la présente recherche est de comprendre le potentiel des liquides synthétiques à base d'ester à faible point d'écoulement pour une application dans les régions froides. Un ester synthétique typique et une huile minérale sont également pris en compte à des fins de référence. Les recherches sont axées sur les phénomènes préclaquagee et les possibilités de régénération des liquides choisis.

La régénération des esters est un sujet d'intérêt majeur pour les propriétaires de transformateurs et les fabricants. Ce sujet est souligné par un nombre limité d'études dans la littérature, sans recommandations solides sur les aspects de régénération des esters. Par conséquent, la présente recherche met l'accent sur les avenues de régénération des liquides diélectriques à base d'ester. Les études se concentrent sur la régénération par adsorbant en utilisant des méthodes de percolation par gravité et par pression.

Les recherches avant la panne visent à comprendre le comportement des liquides à faible viscosité soumis à des contraintes dues à l'impulsion de foudre. Les tests d'impulsion se concentrent sur différentes conditions de terrain, la dégradation thermique et la polarité des ondes de foudre.

Les résultats de la recherche montrent le potentiel des adsorbants à base de silicate de magnésium pour la régénération des esters. À partir des tests préclaquage, il a été observé que la température, le type de champ et la dégradation de l'isolation ont un impact considérable sur les mécanismes de préclaquage et de claquage des liquides diélectriques à faible point d'écoulement.

ABSTRACT

Power transformers are the most critical and expensive among the equipment installed in the electric power grid. The expected service life of a liquid-filled power transformer is generally several decades. This long service life depends mainly on the performance of the oil-paper insulation system. The health monitoring, diagnostics, and prognostics of transformer insulation systems are of critical technical importance. Utility engineers periodically or continuously assess insulation systems (oil/paper) to ensure the safe and efficient operation of transformers. Condition monitoring of transformer insulating oil typically includes diagnostic testing, reconditioning, and regeneration activities. Diagnostic tests (physicochemical and electrical) are performed according to routine and strategic condition-monitoring planning. Reconditioning and regeneration activities generally depend on the state of the insulation degradation, the used life/remnant life, and the degradation products evident in the oil. Physicochemical characterizations (diagnostic tests) are used to assess the condition of the insulation system. Despite periodic monitoring, the degradation of insulation systems is not stoppable: physicochemical characterization activities provide an understanding of the insulation degradation and ensure safe operation thanks to carefully selected preventive measures. Reconditioning and regeneration activities are some of the preventive measures taken based on the level of insulation degradation. These treatments can extend the life of the insulation.

In the last decades, the demand for environmental sustainability and health safety, while withstanding high electric power densities and operating temperatures, has been rising on a global scale. Thus, ester-based dielectric liquids are reported to be potential alternative mineral-insulating liquids. Ester dielectric liquids are known for higher workability and serviceability with improved life of solid insulation systems. However, the application of esters has continued to challenge transformer owners and utility engineers, especially in cold regions. The dielectric behavior and viscosity profile of these new liquids at extremely low temperatures are challenging. On the other side, the end-life behavior of these new liquids is also a key concern to the transformer owners.

The main intent of the present research is to understand the potential of low pourpoint synthetic ester-based liquids for application in cold regions. A typical synthetic ester and a mineral oil is also considered for reference purposes. The investigations are focused on prebreakdown phenomena and regeneration avenues of the chosen liquids.

Regeneration of ester is a topic of key interest to transformer owners and manufacturers. This topic is emphasized by a limited number of studies in the literature with no solid recommendations on the regeneration aspects of esters. Therefore, the present research emphasizes the regeneration avenues of ester-based dielectric liquids. The studies are focused on adsorbent-based regeneration using gravity and pressure percolation methods.

The prebreakdown investigations focus on analyzing the behavior of low pourpoint liquids under lightning impulse conditions. Impulse testing is emphasized in terms of different field conditions, thermal degradation, and the polarity of the lightning waves.

The research findings indicate the potential of magnesium silicate adsorbents for the regeneration of esters. From the prebreakdown testings, it is noticed that the temperature, type of field, and insulation degradation has a considerable impact on the prebreakdown and breakdown mechanism of the low pour point dielectric liquids.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER I
GENERAL INTRODUCTION

1.1. INTRODUCTION

A rapid increase in the global population and industry sector demands a high consumption of electricity. Thus, electric utilities need to over-exploit the fossil fuels such as coal, crude oil stocks, and natural gas to generate surplus power and meet global demand. Such an over-exploitation added to the energy crises across the world and increased the cost of fossil fuels. The increased interest in green energy, net zero emission, and health safety regulations across the global communities demand the search for renewable and sustainable technologies. The international treaty (Paris Accord) on climate change, adopted by 196 countries have laid exclusive targets on the usage of green technologies and has recently stressed the need to limit global warming to 1.5°C by the end of this century at the UN Climate Change Conference in Glasgow, Scotland, in November 2021 [2].

The increase in environmental concerns all over the world has also reached the transformer industry for three decades now [2]. Power transformers are one of the most expensive and important equipment in all three parts (generation, transmission and distribution) of the electric power network. Any failure or outage of a transformer may result in service interruptions and impact the reliability of the electric grid. Most of the power transformers are of oil-immersed type, in which mineral oil (MO) has been used for insulating and cooling purposes since the 19th century [3, 4]. Therefore, abundant data is available on physicochemical characterizations, aging phenomena, and dielectric behaviour of mineral insulating oils in transformers. Apart from its advantageous properties such as thermo-physical, electrical, low cost, and wide availability, the shortfalls like poor fire properties and the non-biodegradable nature of mineral oil contrived the research to look for alternative dielectric liquids. Also, due to, the depletion of MO resources (crude oil stocks), rise in environmental concerns, and to improve the fire safety properties, ester dielectric fluids have been found as the potential alternatives to MO. Ester liquids have a higher flash point, good biodegradability, comparable dielectric strength, higher moisture tolerance[2, 5-7]. However, the higher cost of ester liquids is counterposed with the technical advantages that include affluent properties (as discussed above) and longevity of the insulation system.

The aging of power transformers mainly results in the reduction of the dielectric properties of the insulation system, which is ultimately detrimental. Therefore, it is necessary to focus on the intrinsic behaviour of the insulation system that will lead to degradation. Thus, investigations of the pre-breakdown and breakdown phenomena are essential for ester-filled transformers, which is aimed in the present research. The knowledge on pre-breakdown and breakdown behaviour will be beneficial to insulation engineers and design engineers for updating designing the insulation system of new transformers.

Reconditioning of insulating liquid is a usual practice to extend the service life of the insulation system [8, 9]. The same has been least emphasised in the case of ester dielectric liquids. Hence, the present research is also aimed to focus on the regeneration avenues of ester fluids. An understanding of the regeneration aspects of these new fluids (ester fluids) is important to manage the end-of-life situations and a possible extension of the useful service life of the transformer.

It is to be noted that temperature has a significant impact on the behaviour and performance of these new liquids (ester liquids) [8]. Indeed, the application of these new liquids for transformers serving in cold regions is a challenge to engineers and transformer owners. Therefore, the present research targets low pour point (<-50ºC) ester-based dielectric liquids along with the typical synthetic ester (SE) liquid to explore the above-mentioned aims. This will allow understanding the behaviour of low pour point ester-based dielectric liquids. The innovative part of this research lies in the uniqueness of considering the peculiarities for transformers in cold climates. The pre-breakdown and breakdown under lightning impulse stress as well as new adsorbents for regeneration of esters stand as novel elements to the present research.

1.2. BACKGROUND AND LITERATURE SURVEY

1.2.1. INSULATING MATERIALS IN TRANSFORMERS

The solid-liquid insulation in power transformers constitutes insulating paper and insulating liquids as the insulating materials. Typically, all the live parts of the transformers are wrapped in insulating papers in several layers; the number of layers required can be determined with respect to the transformer design. The insulation paper-wrapped conductors are immersed in the insulating liquid to form a rigid composite insulation system in order to aid the transformer's safe operation. The air voids present in the insulating paper or pressboard result in a decrease in dielectric strength and also a decrease in its heat dissipation capacity. Therefore, when the insulating paper/pressboard is impregnated, the air voids in the solid insulating materials will be filled with liquid, which leads to the improvement of dielectric strength and heat dissipation capacity of insulating paper [3]. To better understand the progress of the transformer insulation system during its operational life, it is recommended to study the structure and nature of insulating materials.

1.2.1.1. LIQUID INSULATION

The insulating liquids should possess good dielectric strength, good thermal properties, low viscosity, low dielectric dissipation factor, high availability, and better chemical stability in order to meet the qualities of being a suitable insulant for a transformer [2]. Mineral oil (MO) which possesses good dielectric properties, high availability, low cost, low viscosity profile, better cooling properties, and good oxidation stability, is the most widely used dielectric liquid. MO has been used as the main insulating liquid since the beginning of the transformer industry [2]. However, with the depletion of the crude oil resources, increase in environmental concerns, and requirements to improved fire safety properties, there is a growth in interest in looking for alternative dielectric fluids for the transformers, with high flash and fire points, low toxicity, highly biodegradable nature [2]. After several years of research on this topic, ester dielectric fluids came into existence with high flash and fire points, good biodegradability, high dielectric strength [2, 10]. However, poor oxidation stability, viscosity profile and high pour point, are limiting the wide application of natural esters and synthetic esters are expensive [5]. It is to be noted that any single liquid may not possess all the above-mentioned properties. However, it is always better to consider operational characteristics, environmental safety, and cost benefits while choosing a dielectric fluid for transformers [10]. The characteristics of the main insulating liquids for transformer insulation are shown in Table 1.

TABLE I.1. Characteristics of the main insulating liquids used in transformers [6, 9, 11, 14].

Characteristic	Mineral Oil	Silicone Oil	Synthetic Esters	Natural Esters
Acidity (mg KOH/g)	< 0.01	< 0.01	< 0.03	< 0.03
Fire Point, (°C)	180 - 185	340 - 350	300 - 322	350 - 360
Pour Point (°C)	≤ -40	< -50	< -40	< -10
Flashpoint (°C)	100 - 170	300 - 310	250 - 275	315 - 330
Viscosity (mm^2/s) at 20°C Viscosity (mm^2/s) at 40°C	22 3 - 16	54 35 - 40	70 14 - 29	97 16 - 37
Breakdown voltage (kV) at 2.5 mm	30 - 70	35 to 70	45 - 70	82 - 97
Dissipation factor (tan delta) at 90°C	< 0.002	< 0.001	< 0.006	0.0014
Density at 20°C g/ml	Max 0.895	0.96	0.97	Max 1.0
Interfacial Tension (mN/m)	40 - 45	-	35 - 39	36

Ester-based Liquids for Cold Regions: To accept biodegradable liquids in transformers in cold climatic regions, three main parameters are to be critically considered: pour point, viscosity, and solidification temperature. The pour point is a temperature below which the liquid loses its fluidity and starts freezing. At that particular temperature, the viscosity of that liquid starts to increase, increasing the internal temperature and pressure of a transformer, and therefore ultimately impacting its useful life. Additionally, it is recognized that the water saturation limits of ester liquids are higher than that of MO at all temperatures. The low water saturation limit of MO may be detrimental to its breakdown strength. Consequently, this may lead, under certain circumstances to explosions during cold starts [7]. Therefore, low pour point liquids must be investigated for water behaviour under various conditions. The properties of some low pour point liquids available in the market are summarized in Table. 2.

TABLE I.2. Properties of some low pourpoint synthetic ester liquids [7]

Property	MIDEL 7131	MIDEL ICE	NYCODIEL 1233
Colour, ASTM D 1500	125 (ISO 2211)	Pale yellow	80
Density(kg/m3), ASTM D 1298/ISO 3675	0.97 to 0.98 @20 °C	0.915 @20 °C	0.95 @20 °C
Viscosity(cSt) @40°C, ASTM D445	29	7.7	16.1
Interfacial tension (mN/m), ASTM D971	-	26.0	-
Acidity (mgKOH/g), ASTM D974	< 0.03	<0.03	0.01
Pour point (ºC), ASTM D 97 / ISO 3016	-56	-75	<-65
Flash point (ºC), ASTM D92 / ISO 2719	260	198	248
Fire point (ºC), ASTM D92 / ISO 2592	316	220	284
Breakdown voltage (kV), ASTM D1816 /IEC 60156	>75	> 75	65

1.2.1.2. SOLID INSULATION

The solid insulating materials used in transformers are paper, pressboard, and crepe paper. All these solid insulants are extracted from cellulose materials that originated from the plants. Cellulose insulation has been widely used as transformer insulation due to its good mechanical and electrical properties in addition to its high availability [12]. Its excellent dielectric strength when impregnated in insulating liquid has become widely accepted as a pillar of electrical insulation [3]. Solid insulation (insulation paper/pressboard) is used as a mechanical separator of the active parts of a transformer [4, 13, 14]. In addition, insulation paper degradation, which is analyzed indirectly through different tests performed in the laboratory, can merely determine the end-of-life criteria of transformer insulation. There are two types of solid insulation which are differentiated based on their source of extraction, cellulose-based and synthetic insulating papers. There are various cellulose-based papers like kraft paper, cotton paper, hemp, and manila. The papers like cotton, manila, and hemp are less considered in power transformer insulation because of their high degradation rate. However, kraft paper has been widely used in power transformer insulation due to its good dielectric strength when impregnated in insulating liquids [4]. Some more advancements in this research led to the invention of Thermally Upgraded Kraft (TUK) to improve thermal stability by adding nitrogen-based stabilizing agents.

Thermally Upgraded Papers: During 1950s, various researchers related to the transformer/paper manufacturing units of that era came up with thermally upgraded kraft paper as a solution to improve the paper's life [15]. TUK paper is also prepared from cellulose base like any other kraft paper. However, they are treated by some chemical methods or by adding nitrogen-based stabilizing agents (1 to 4 %) to enhance their thermal stability in order to improve the life of transformer insulation. The insulating paper is approved as a thermally upgraded paper if it attains 50% retention in tensile strength after being aged at 110°C in a sealed tube for 65,000 hours or any other temperature or time, which satisfies the Arrhenius equation. Since the 1950s, TUK paper has been introduced as an insulating paper in transformers [16, 15]. Later in the 1960s, the merits of these treated papers are recognized by the National Electrical Manufacturers Association (NEMA). It is mentioned that the 55°C oil rise temperature is the norm for the normal or non-upgraded paper, whereas it is 65°C oil rise for TUK paper [3, 12, 15].

Insuldur™ process is the most commonly used thermal upgrading process because the nitrogen content present in the paper stays active for a longer duration during accelerated aging whereas this is not the same in upgrading papers by chemical modifications [16]. The insuldur upgrading process involves adding nitrogen-based compounds in the paper [15]. It is known that the composition of kraft does not contain nitrogen; therefore, the number of upgrading agents will be identified by measuring nitrogen in the thermally upgraded paper. Arroyo-Fernández et al [17], have performed the aging studies at 170°C on TUK papers of three different nitrogen contents (1.2, 2.6, and 4.4). At the end of the aging, it is understood from their research that the increase in nitrogen contents in kraft papers improves the life of the cellulose insulation. The papers with more than 2.6% of nitrogen show lower improvement in degradation rate when compared to the papers with 1.2 to 2.6% of nitrogen [17].

1.2.2. PRE-BREAKDOWN PHENOMENA IN TRANSFORMER INSULATING LIQUIDS

The study of electric discharge in liquids starting from initiation until breakdown occurs is referred to as the pre-breakdown phenomenon. This happens when a sudden initiation and propagation of electric energy (current) takes place through the bulk volume of the liquid between two electrodes (a high-voltage electrode and a ground electrode) under the influence of an electric field. This continuous electric discharge (also referred to as a streamer) in an insulating medium when builds as a bridge in between the two electrodes (separated by an insulating medium), leads to a complete electrical breakdown [8, 18]. The electric breakdown in insulating liquid involves many stages such as inception, propagation, and a complete breakdown. The events that occurred prior to the breakdown process are known as the pre-breakdown events, which are also termed streamer characteristics. Not all initiated streamers cause an electrical breakdown in liquids. Some streamers terminate before reaching the grounded electrode, which is called partial discharge. Partial discharges might not cause a severe failure in the transformer insulation. But the continuous occurrence of partial discharges and partial discharging activity followed by arcing may cause severe damage to the insulation system as well as the transformer. Thus, it is of high importance to monitor and locate the partial discharging activity in the HV apparatuses. To ensure its protection, the mechanisms of streamers in insulating liquids and the conditions that favoured the formation and initiation of streamers in the liquid medium are to be keenly investigated. To this line, various researchers have investigated the pre-breakdown behaviour in transformer insulating liquids [8, 18, 19-28]. The major streamer characteristics include inception voltage, propagation time, stopping length, streamer velocity, streamer accelerating voltage, and streamer shape. The same is reported for various insulating liquids in the literature and a few are discussed in the subsequent discussion. Research on pre-breakdown phenomena in mineral oils has been reporting for years and the summary of which can be found in [19, 29].

A working group formed by the IEEE Technical Committee on liquid dielectrics has summarised the pre-breakdown phenomena in ester-based dielectric liquids vis-à-vis mineral oil [30]. It is to be noted that the prime factors influencing the pre-breakdown and breakdown behaviour are the type of electrode configuration (gap, radius of the point or needle electrode), type of voltage (nature, magnitude, and duration), and nature of the electric field. The pre-breakdown phenomenon of synthetic esters and natural esters is experimentally investigated at different inter-electrode gap distances in [30]. It is observed that streamer inception voltages of synthetic esters are comparable to that of the mineral insulating oils. However, streamer propagating voltages are faster in ester-based oils as compared to mineral oils. In [31], the stopping length of streamers in ester liquids and mineral oils has been compared for negative and positive polarity streamers. A longer stopping length of streamers is observed by the authors in natural esters as compared to that of mineral oils. Streamer velocities of ester liquids and mineral oils are experimentally reported in [32-34]. The behaviour under AC stress is a typical approach to investigate the prebreakdown activity of the transformer liquids because of the operating conditions of the transformer. However, the behaviour under impulse voltages is critical since transformers are generally located outdoor and therefore constantly exposed to environmental conditions. Thus, it is important to understand the behaviour of insulation systems under lightning impulse voltages. A standard impulse voltage rapidly rises in 1.2 ± 30% μs to its peak and falls (decay) in 50 ± 20% μs to the half of its peak. The impact of the AC and lightning impulse stress on liquids has been reviewed and reported in [19, 7, 8]. Another important parameter here, is the polarity of lightning strokes. It is known that 90% are negative in polarity in temperate countries and are typically considered to investigate the prebreakdown behaviour of transformer liquids [35]. However, the positive polarity strikes are more energetic and impactfully detrimental to the system [19, 36]. In addition, the nordic climates and snowy conditions favor the formation of the development of positive polarity lightning strikes [36].

Thus, it is important to understand the impact of impulse polarity and low temperatures on the breakdown behaviour of the insulation system.

Other factors that influence the streamer characteristics include, chemical composition (type of the liquid, purity, and additives) and state of the liquid (fresh, aged) [37]. Several investigations were carried out with the help of the latest optical technologies to visualize the pre-breakdown events in esters [38]. The chemical composition (type) of insulating liquid shows a significant effect on the propagation characteristics of the streamer. Chemical bonds and functional groups of the liquid have an impact on the electron affinity and ionization process. This influences the streamer initiation and propagation [29]. Also, the intensity of the optical emission and streamer velocity vary based on the type, viscosity, and temperature of the liquid [39]. Furthermore, it is reported that the positive needle tends to initiate fast-filamentary streamers in chlorocyclohexane when compared to that of the actual cyclohexane [40]. Also, it is established that the negative polarity (with tip radii > 10 μm) tends to develop a bush–shaped streamer in saturated hydrocarbon liquids. For pure aromatic liquids, negative streamers can also be tree-shaped [29].

The electrode geometry is another fundamental parameter influencing the streamer characteristics and pre-breakdown behaviour of an insulating liquid. The streamer inception, propagation, velocity, and breakdown are highly dependent on the duration and magnitude of the applied voltage and electric field. The electric field is something that is controlled by the shape of the electrode, radius of the electrode, and distance between the electrodes. Therefore, the electric field influences the shape and propagation nature of the streamer [41]. For smaller gaps, the intensity of the electric field at the needle tip is higher and aids the initiation of streamer for moderate values of the applied voltage. Similarly, for large gaps, the intensity of the electric field is lesser (for similar electrode tip) and high applied voltages are required to initiate the streamer. However, it is important to understand the impact of no-uniform field (which is typically reported) vis-à-vis the quasi uniform field on the breakdown behaviour of the new dielectric liquids.

Temperature has an impact on the physicochemical properties of the liquid and streamer behaviour. However, the influence of temperature on the pre-breakdown phenomena is least emphasized in the literature. Recently, the influence of temperature on typical natural ester liquids was reported in [42]. It is verified that partial discharge characteristics are temperature-dependent. However, this depends on the type and age of the liquid. The streamer characteristics for synthetic esters have been investigated at different temperatures (20, 40, 60, and 80 ºC) [43]. It is reported that, with an increase in temperature, stopping length is noticed to be reduced while the partial discharge magnitude decreased. However, further investigations on a wide range of temperatures especially low-temperature measurements, are to be performed to understand the impact of temperature on the pre-breakdown phenomena of ester liquids in cold regions.

The age of the insulating liquid is evident by the presence of decay particles, water, acids. These particles act as local conducting particles and may highly aid the streamer properties. However, the influence of aging on the pre-breakdown behaviour is less emphasized by the researchers. Recently, in [37, 44] the influence of thermal aging on pre-breakdown behaviour was reported. It was verified by the authors that the thermal degradation of the liquids has a significant influence on the streamer properties. However, there is a need for further detailed measurements to understand the impact of thermal aging on the pre-breakdown phenomena of ester liquids under impulse conditions and low temperatures.

1.2.3. REGENERATION OF TRANSFORMER INSULATING LIQUIDS

It is known that the degradation of transformer oil-paper insulation evidently introduces water (free and dissolved), dissolved gasses, acids, polar compounds, colloids (from cellulose and oil degradation), free radicals, peroxides, dust, and cellulose fibers [45]. The presence of these particles influences the properties of the liquid and is detrimental to the insulation system. Timely removal of these decay particles will keep the insulating liquid close to pristine conditions while protecting the dielectric aspects. Therefore, it is an industrial practice to treat the insulating liquid for improving its properties and useful service life. The procedure adopted for improving the liquid properties is referred to as reclamation or regeneration and is generally noted as decontamination of the liquid. This involves one or more steps that include dehydration, filtration, sedimentation, centrifuging, and adsorption with an aim to removing moisture, acids, colloids, and other impurities. In the case where regeneration is not possible or not economical (highly aged liquids) the liquid is recycled before using it by re-refining. Re-refining is a process of exhaustive removal of dissolved chemical contaminants and other contaminants in the oil for use in other applications [46]. It is to be noted that insulation liquid's degradation is reversible to a certain level with the removal of the said decay particles. Whereas insulating paper degradation is an irreversible depolymerization process. However, it is observed that solid insulation aged in oil that is periodically treated is less degraded than the one that is aged in the oil that is not treated [47, 48].

Thus, with the aim of keeping the oil in pristine conditions and reducing the degradation rate of solid insulation, oil conditioning is important for the transformer owners and condition monitoring engineers. The IEEE Guide for the "Reclamation of mineral insulating oil and criteria for its use" says Fuller's earth may be used to recondition in-service mineral insulating oils [6]. The research on reconditioning of ester liquids is still at the early stage and investigations for potential adsorbents are less emphasized. In [49], a batch of different materials including clays and adsorbents have been investigated for conditioning of insulating liquids. However, there is no evidence on the type of adsorbents and ester liquids. The IEEE Guide (C57.147-2018) for acceptance and maintenance of natural ester insulating liquids claims that magnesium silicate, magnesium aluminum phyllosilicate, activated alumina, and bauxite-based adsorbents may improve the conditioning process [50]. It is reported that magnesium silicate-based adsorbents are widely accepted to remove acids and polar compounds from the used cooking oils [51]. Also, magnesium silicate-based adsorbent has been reported to be effective for a typical natural ester dielectric fluid as compared to the other clays [52].

It is to be recalled that the reclamation is practised by different treatment media namely, sorbents, molecular sieves, fine filter papers, in exchange media, scavenging media and membranes. Also, by different approaches including, percolation (pressure and gravity), filtration, and centrifuging. The same are summarised in the IEEE standard C57.637 [6], which is currently under major revision with an aim to expand it for ester liquids. Adsorbent based reclamation under vacuum is known for efficient and high regeneration rate. Similarly, the percolation method is popular approach as it involves vacuum and additional filtering/drying chambers. The critical evaluation of adsorbent based reclamation is demonstrated using different adsorbents in [49], however, the investigation is limited to mineral insulating oils alone. In [53], reclamation of natural ester liquids based on adsorbents is reported. Due to higher viscosity and gelling aspects of aged natural esters, further evaluations are to be performed on the feasibility of reclaiming natural esters. The end life behaviour of synthetic esters vis-à-vis mineral oil is reported in [54, 9, 48, 55, 56] by making use of centrifugal separation and Fuller's earth filtration approaches. It is observed that the occurrence of colloidal particles is much higher in mineral oils than in the synthetic esters. The degradation of synthetic ester is majorly governed by the soluble particles. This is because esters are polar in nature and most of the oxidation by-products being polar in nature, dissolve in esters. Also, due to the hydrophilic nature of esters, cellulose degradation is greatly controlled and the scope for cellulose-based colloidal particles is lesser than mineral oils. In [57], it is reported that magnesium-based adsorbents may be suitable for the regeneration of esters. However, the reclamation of synthetic esters based on adsorbents has been less emphasised in the literature. Therefore”, it is important to explore adsorbent based reclamation with potential percolation methods. It is hoped that such investigations will improve the topic “regeneration of esters” towards establishing an optimal and efficient reclamation procedures that act in extending the service of the insulation systems.

1.3. PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Application of ester liquids in cold regions is still at the early stage. Thus, this research is focused on the application of ester dielectric fluids for transformers in cold regions. From a comprehensive literature survey, it is observed that there is significantly limited published data on pre-breakdown phenomena of low pour point ester fluids. In addition, the influence of temperature and liquid aging on partial discharge (PD) characteristics is least emphasized in the literature. Also, the impact of impulse polarity and filed nature are not yet reported for the case of low pour point liquids vis-à-vis typical synthetic esters and mineral oils. Therefore, it is interesting to study the pre-breakdown phenomena of the ester liquids to understand ester-filled transformers' breakdown behaviour in cold regions. The information on pre-breakdown phenomena will be useful to insulation engineers and design engineers in improving the designed life of transformers.

Along with other impacts, the decay products that evolved with respect to the liquid degradation, also significantly influences the dielectric behaviour. Hence, reconditioning of ester liquids is another important topic that is of important concern for the transformer owners and is very less focused by the researchers. The regeneration avenues of ester-based liquids are at the infant stage which is investigated by a very few researchers. Understanding the end-life behaviour of esters brings added advantages to transformer owners for the application of these new liquids. The knowledge on the regeneration of ester liquids will be helpful for maintenance engineers and transformer owners.

At a glance, much lesser knowledge is available on application of esters in cold regions hence the research is focused on the low pour point ester-based liquids. Therefore, the objective of this research is to investigate the pre-breakdown phenomena and regeneration avenues of ester liquids for usage in transformers serving in cold climatic regions. To address the above-stated global objective, the research objectives below have been considered in the present thesis.

Objective 1. To investigate and understand the regeneration avenues of ester fluids.

- ✓ To understand the possibility of the regeneration of ester liquids with pressure and gravity percolations.
- ✓ To investigate the use of magnesium silicate-based adsorbents for reclamation of synthetic ester-based liquids.

Objective 2. To investigate the pre-breakdown and breakdown behavior of low pour point ester dielectric liquids.

- ➢ Under standard lightning impulse stress
  - ✓ To investigate the influence of thermal aging.
  - ✓ To investigate the influence of polarity (negative and positive).
  - ✓ To investigate the influence of nature of electric filed (non-uniform and quasi uniform).

1.4. ORIGINALITY OF THE RESEARCH

The key originality of this research lies in the uniqueness of considering the peculiarities for transformers in cold climates with a focus on ester based dielectric liquids. The pre-breakdown and breakdown analysis at low temperatures under AC stress, and analysis under lightning impulse stress as well as new adsorbents for regeneration of esters are novel elements of the present research. The key contributions that are of interest are detailed below:

These findings add to limited knowledge on the application of esters in cold countries and allow insulation designers to estimate the dielectric behaviour of the low pour point synthetic ester liquids under lightning conditions.

The reclamation of ester liquids is critical topic of research that is least explored and is a much need to the utility engineers and transformer owners. The present research reports the experimental evidence on the viability of the adsorbent based reclamation of synthetic ester liquids with a new class of adsorbents. This may open the door to a significant impact not only on life time extension, but also on decarbonization objectives. The latter represents a significant volume of circular economy which will reduce the ownership costs of these major devices.

At a glance, the results reported through this research adds to the arguments in favour of replacing mineral oils in power transformers.

1.5. THESIS ORGANIZATION

The present thesis is organized into the following chapters to present the research work carried out in this project. It is to be mentioned that the current thesis is prepared in the "thesis by articles" format.

- Chapter 1 (Introduction): A brief introduction to the subject of the present research focus is highlighted and discussed. This chapter also presents the general background, state of the art, and objectives of the present research.
- Chapter 2 (Article 1): "Reclamation of Synthetic Ester Dielectric Liquids by Pressure and Gravity Percolation Methods". This article provides the results of the experimental study on the reclamation of two low pour point synthetic ester fluids and a typical synthetic ester liquid using magnesium silicate-based adsorbents by employing pressure and gravity percolations. The experimental results also include mineral-insulating oil for a baseline reference.
- Chapter 3 (Article 2): "Prebreakdown and Breakdown Behaviour of Low Pour Point Dielectric Liquids Under Negative Lightning Impulse Voltage". In this article, experimental investigations on the prebreakdown and breakdown phenomena of low pour point insulating liquids under negative lightning impulse voltage are reported. The tested liquids include mineral oil, a typical synthetic ester, and two low pour point synthetic esters. The non-aged and aged samples were subjected to lightning impulses using a point-plane electrode arrangement to understand the influence of thermal aging.
- Chapter 4 (Article 3): "Analysis of Breakdown Voltage of Low Pour Point Synthetic Ester Insulating Liquids under Lightning Impulse Voltage of both Polarities". In this article, lightning impulse breakdown behaviour of two low pour point synthetic ester liquids is presented in

comparison to a typical synthetic ester and mineral oil for both positive and negative polarities. A detailed breakdown behaviour analysis of the four test liquids under a non-uniform field (medium gap, point-plane electrode system) and quasi-uniform field (smaller gap, U-plane electrode system) is envisaged.

- Chapter 5: Finally, major conclusions made from the present research and recommendations for future work are presented.

CHAPTER II

RECLAMATION OF SYNTHETIC ESTER DIELECTRIC LIQUIDS BY PRESSURE AND GRAVITY PERCOLATION METHODS

Article submitted to

IEEE Transactions on Dielectrics and Electrical Insulation

RECLAMATION OF SYNTHETIC ESTER DIELECTRIC LIQUIDS BY PRESSURE AND GRAVITY PERCOLATION METHODS

Abstract

Knowing the tremendous demand for electricity and higher operating voltages, high stress is imposed on the transformer insulation system. Condition-based maintenance and liquid decontamination are activities for risk assessment and service life extension of transformer insulation systems. Hence, it is important to explore the reclamation of the new biodegradable liquids. It is known that adsorbent-based reclamation is a prominent approach to treating insulating liquids. The present article provides the results of the experimental study on the reclamation of two low pour point synthetic ester fluids and a typical synthetic ester liquid using magnesium silicate-based adsorbents. The experimental results also include mineral-insulating oil for a baseline reference. All four liquids were subjected to accelerated aging under open beaker conditions in the presence of cellulose. The aged liquids were then regenerated by pressure and gravity percolations with two magnesium silicate-based adsorbents. Physicochemical and electrical characterizations were conducted on both the feed and filtrate. It is inferred that magnesium silicate-based adsorbents have some potential for reclamation of synthetic esters in removing the polar compounds that evolved with the liquid's service life.

2.1. INTRODUCTION

Transformers are considered the heart of the electric power network. Since the early 1900s, the insulation systems for these high-cost machines have typically consisted of solid insulation, such as cellulose and mineral oils derived from crude petroleum [1]. In the last decades, the demand for environmental sustainability and health safety, while withstanding high electric power densities and operating temperatures, has been rising on a global scale. Thus, ester-based dielectric liquids are reported to be potential alternative mineral-insulating liquids [1, 2]. Ester dielectric liquids are known for higher workability and serviceability with improved life of solid insulation systems [2]. However, the application of esters has continued challenging the transformer owners and utility engineers, as summarised in [3, 4]. Meanwhile, various researchers have reported the behavior of the ester dielectric fluids concerning viscosity [5], streamer behavior [6], and condition monitoring aspects [3]. The literature has widely reported the degradation behavior, compatibility with other transformer materials, dielectric, and other physiochemical aspects [2, 7, 8]. The freezing point and the viscosity profiles of ester liquids have been a concern to various transformer manufacturers. In our recent studies, the behavior of low pour point ester-based liquids has been reported [9-11]. The studies concerning the degradation behavior [9], the influence of aging on the ionizing streamers [10], and behavior under lightning impulses [11] have been evaluated by the author's group. It was found that low pour point liquids are potential candidates for transformers serving in cold regions. However, further investigations must be carried out to recommend the same to the industry.

Another major challenge in dealing with the state of the art of ester liquids is the decontamination avenues of these new dielectric liquids. The decontamination may be referred to as degassing, drying, regeneration, and reclamation of insulating liquid. Degassing and de-moisturizing (drying) are straightforward methods, and the procedures used for mineral oils can be easily adapted for esters, provided that the process remains physical or mechanical. However, the methods involving chemical treatments need to be reconsidered and investigated before application to ester-based dielectric liquids. The regeneration and reclamation methods, which typically involve treating with filtering media, ad/absorbents, and molecular sieves, are still a challenge in the case of ester liquids. While Fuller's earth is the most successful candidate for reclaiming mineral oils, the same is challenging for ester liquids [12]. The regeneration of natural esters is challenging because natural esters produce polymerized aging products, gelling under oxidation. Thus, making the liquid too viscous due to thermal aging. The feasibility of reclaiming synthetic esters is still explorative, and the potential procedures and materials are challenging.

It is to be recalled that the reclamation is conducted by using different treatment media, namely, sorbents, molecular sieves, fine filter papers, ion-exchange media, scavenging media, and membranes. Different approaches are also used, including percolation (pressure and gravity), filtration, and centrifuging. The same are summarised in the IEEE standard C57.637 [6], which is currently under major revision intending to expand it for ester liquids [12]. Adsorbent-based reclamation under vacuum is known for its efficient and high regeneration rate. Similarly, the percolation method is a popular approach as it involves a vacuum and additional filtering/drying chambers. The critical evaluation of adsorbent-based reclamation is demonstrated using different adsorbents [13]. However, the investigation is limited to mineral-insulating oils alone. In [14], the reclamation of natural ester liquids based on adsorbents is reported. As mentioned, due to the higher viscosity and gelling aspects of aged natural esters, further detailed evaluations are to be performed on the feasibility of reclaiming natural esters. The end-life behavior of synthetic ester vis-à-vis mineral oil is reported in [15, 16] by making use of centrifugal separation and Fuller’s earth filtration approaches. It is observed that the occurrence of colloidal particles is much higher in mineral oils than in synthetic esters. This is because esters are polar in nature, and most of the oxidation by-products, being polar in nature, dissolve in esters. Also, due to the hydrophilic nature of esters, moisture-based cellulose degradation is greatly controlled, and the scope for cellulose-based colloidal particles is lesser than in mineral oils.

In IEEE Std. C57.147 [17] and [18], it is reported that magnesium-based adsorbents may be suitable for the regeneration of esters. However, the literature has less emphasized the reclamation of synthetic esters based on adsorbents. Recently, the authors' group has investigated the feasibility of reclaiming synthetic esters by pressure percolation method with magnesium silicate-based adsorbents [19]. From the preliminary findings, it was noticed that the magnesium silicate-based adsorbents have the potential to reclaim synthetic esters. This paper presents the results of a study on two magnesium silicate-based adsorbents used for the reclamation of low pour point synthetic esters and typical synthetic ester liquids. In addition, the studies span two percolation methods, namely gravity and pressure percolations.

2.2. EXPERIMENTAL

2.2.1. MATERIALS

2.2.1.1. INSULATING LIQUIDS AND THERMAL AGING

In the present study, four insulating liquids are considered as test liquids: mineral oil (MO), typical synthetic ester (SE1), and two low-pour-point synthetic esters (SE2 and SE3). All the test liquids are subjected to accelerated thermal aging under an open beaker condition in a conventional oven based on a modified ASTM D1934-20 standard at 150°C for 8 weeks, with a ratio of 1:20 (kraft paper: oil). A typical cellulose kraft paper was employed; its degree of polymerization dropped from 1014.2 to 219.7, 462.61, 268.2, and 443.6 for papers aged in MO, SE1, SE2, and SE3, respectively, following thermal aging.

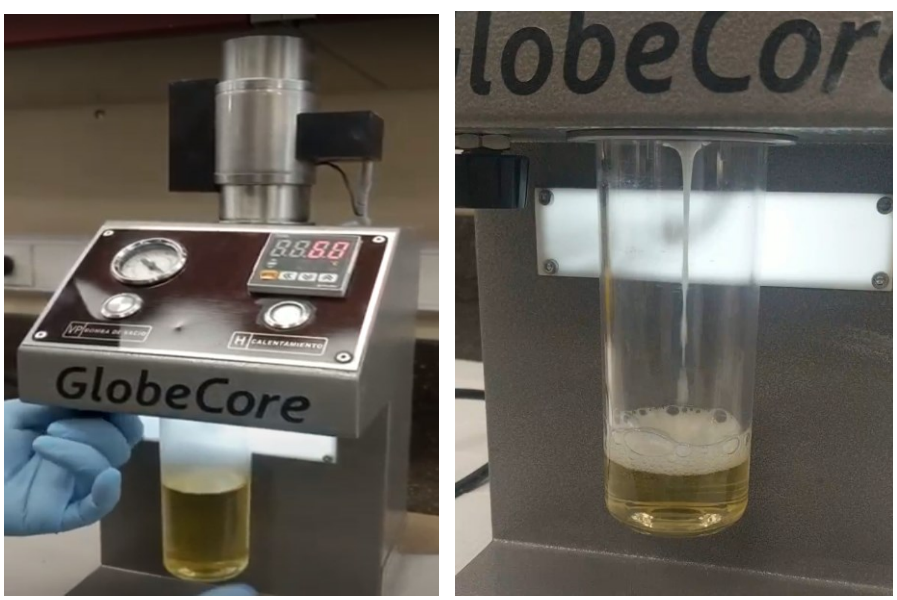
2.2.1.2. ADSORBENTS

Despite the ambiguity in deciding the adsorbents for ester fluids, as per IEEE Std. C57.147, magnesium silicate may be used as a possible adsorbent to enhance the reclamation performance in ester liquids [17, 18]. Therefore, magnesium silicate-based adsorbents Magnesol® (AD1) and Magnesorb® (AD2) from DALLAS have been adopted for this study.

2.2.2. RECLAIMATION METHODS

2.2.2.1. PRESSURE PERCOLATION METHOD

The pressure percolation apparatus (GlobeCore®, CMM-0,001U) is equipped with room for the adsorbent, referred to as a pod, which can be heated to the desired temperatures. This pod has to be half-filled with the adsorbent, leaving the remaining room for the feed oil (the oil to be treated). The other end of the pod is connected to a vacuum pump that creates the desired pressure on the feed oil. A perforated metal plate and a synthetic fiber mesh that comes with the apparatus is placed at the bottom of the pod to block the passing of the adsorbent particles with the oil. The feed oil under pressure then passes through the adsorbent bed, and the filtrate is collected in the collector; a view of the setup and the filtrate collector is shown in Figure II. 1. The adsorbent pod is half-filled with the adsorbent, which is preheated at 60°C, and the preheated insulating liquid (at 60°C) is passed through the adsorbent pod with the help of vacuum pressure. The recovered liquid (filtrate/final liquid) samples are characterized, and the results are compared to the aged and unaged liquid properties to assess the reclamation efficiency.

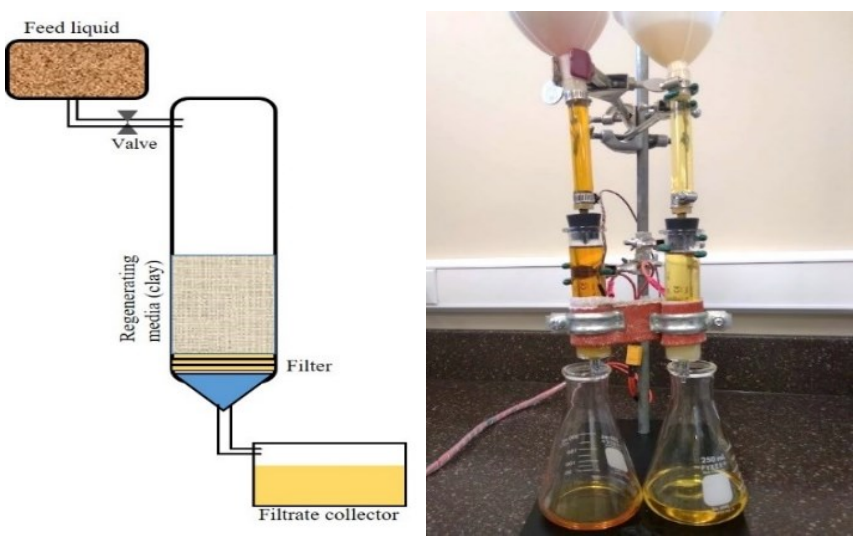


(a) (b)

Figure II.1. Setup used for pressure percolation.

2.2.2.2. GRAVITY PERCOLATION METHOD

The reclamation process by gravity percolation is performed by gravity as the hydrostatic head of an oil column that makes the oil pass through an adsorbent column. A schematic of the regeneration unit by gravity percolation is shown in Figure II. 2(a), which may be visualized as three tanks at different levels. The tank on the top is used as a reservoir to hold the service-aged oil; the middle tank has the filter placed below the adsorbent bed; and the bottom tank collects the filtered oil. The middle tank has a strainer-type bottom that acts as a filtering unit. The setup used for the present research is shown in Figure II. 2(b). The adsorbent room (50 ml syringe) is filled with 15 g of adsorbent and is heated at 60°C for 60 minutes. This process allowed any moisture in the adsorbents to escape and activated the adsorbent surface. To avoid passage of the adsorbent particles through the filtrate, a filter paper (5 microns) is placed at the outlet of the syringe. Two drops of the dehydrated unused test liquid are dropped on the filter paper to completely block the passage of the adsorbent particles. Later, 230 ml of feed liquid preheated at 30°C is introduced on the adsorbent, and the liquid is passed through the adsorbent bed under gravitation. A close view of the adsorbent bed in the syringe is shown in Figure II. 2(c).



(a) Schematic (b) Setup

(c) Adsorbent bed

Figure II.2. Setup used for gravity percolation.

2.3. RESULTS AND OBSERVATIONS

The results of the reclamation with magnesium silicate-based adsorbents are reported in this section. The discussions are separated by the two percolation methods used for reclamation, namely pressure percolation and gravity percolation. The results are compared with the aged and un-aged liquid properties to assess the reclamation efficiency.

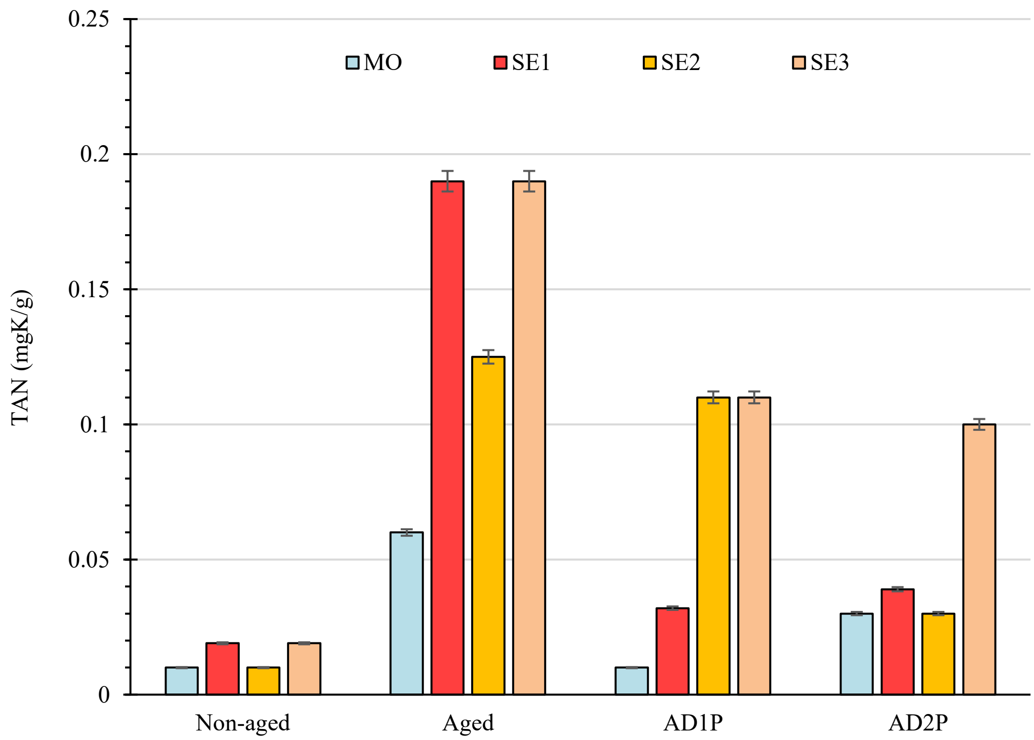
2.3.1. PRESSURE PERCOLATION (P)

The results of the changes in the liquid properties after pressure percolation are presented in this subsection. In the results, AD1P represents adsorbent 1 with pressure percolation, and AD2P represents adsorbent 2 with pressure percolation.

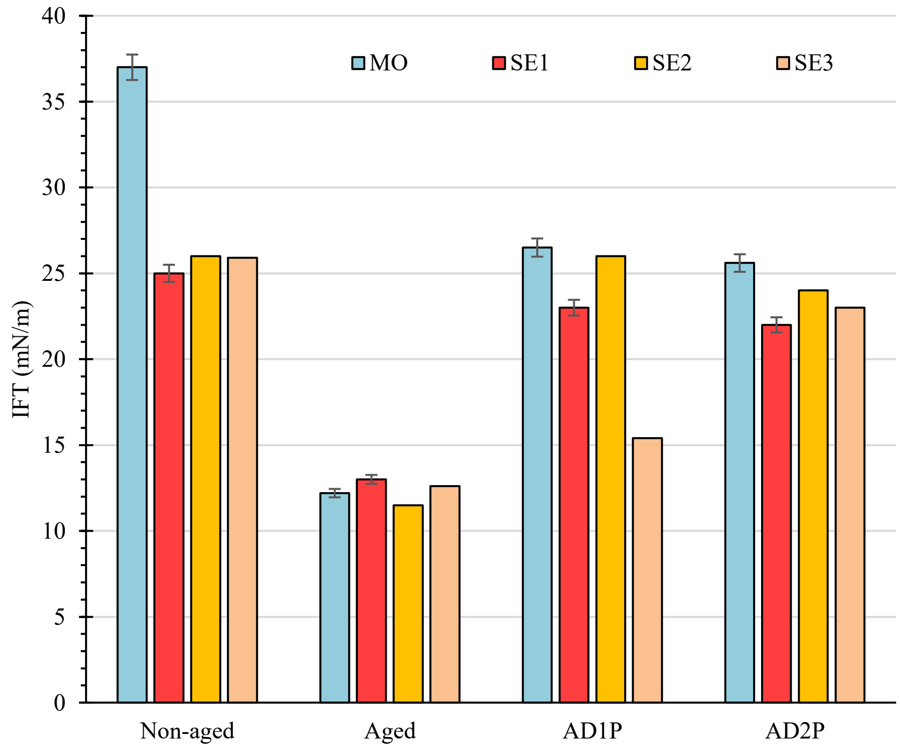
Detailed results on this method, including acidity, interfacial tension, moisture, and breakdown voltage measurements, are reported in the literature [19].

Total Acid Number and Interfacial Tension

Total acid number (TAN) and interfacial tension (IFT) are widely accepted aging markers that demonstrate the aging of the liquid [64]. Therefore, TAN and IFT are measured before and after the reclamation with two adsorbents, AD1 and AD2, and are represented in Figure II. 3. The non-aged samples are also taken into consideration as a reference. The results shown are the average of three measurements and the error bars are the standard deviation.



(a). Acidity.



(b). Interfacial Tension.

Figure II.3. Variations in acidity and interfacial tension of various liquids with reclamation by pressure percolation

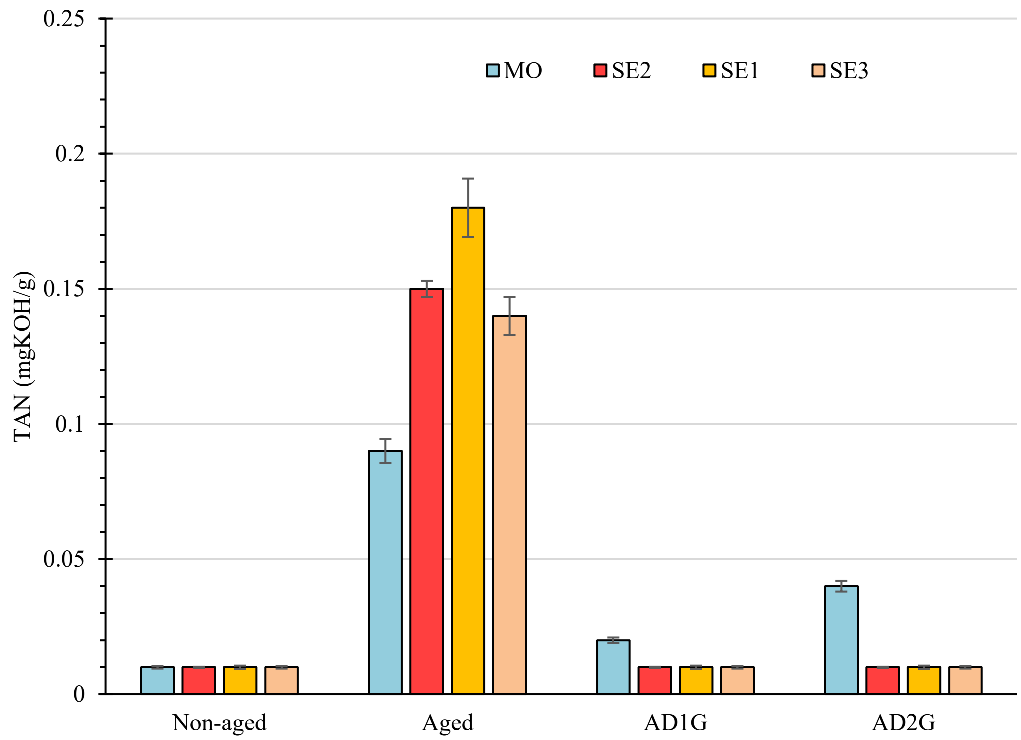
As expected, thermal aging has increased the acidity of the fluids, where the acidity of esters is higher than that of MO. This may be explained by the hygroscopic nature of the ester fluids, which lets them actively participate in hydrogen bonding as hydrogen acceptors [1, 2, 4]. The reclaimed samples show improvement in the context of TAN and IFT within a single pass. TAN's obtained values are in line with the established literature and within the acceptable limits for mineral oils [20, 21]. The improvement in TAN with the treatment indicates the potential of the adsorbents (AD1 and AD2) in reducing the oxidation decay products from the aged liquids. However, the MO IFT values are not within the acceptable limits of unused liquids mentioned in [21] for a single pass, which is 30 mN/m. Simultaneously, ester fluids showed a promising improvement in the IFT values after reclamation with AD1 and AD2 by achieving values close to their original condition. It is observed that AD1 is more efficient than AD2 in removing the soluble polar contaminants and oxidation products from ester fluids. The same is further verified by the moisture reduction and breakdown voltage improvement with treatment. The dielectric strength is noted to decrease significantly with the reclamation by both AD1 and AD2. Samples were not preconditioned before dielectric testing. Therefore, the pressure applied for percolation has carried the adsorbent particles to the filtrate, which act as local conducting particles. On the other hand, the water content in liquids increased after reclamation. This may be because the liquids carry the moisture in the adsorbents. A detailed discussion of the results of the breakdown voltage and water content measurements is presented in [19].

2.3.2. GRAVITY PERCOLATION (P)

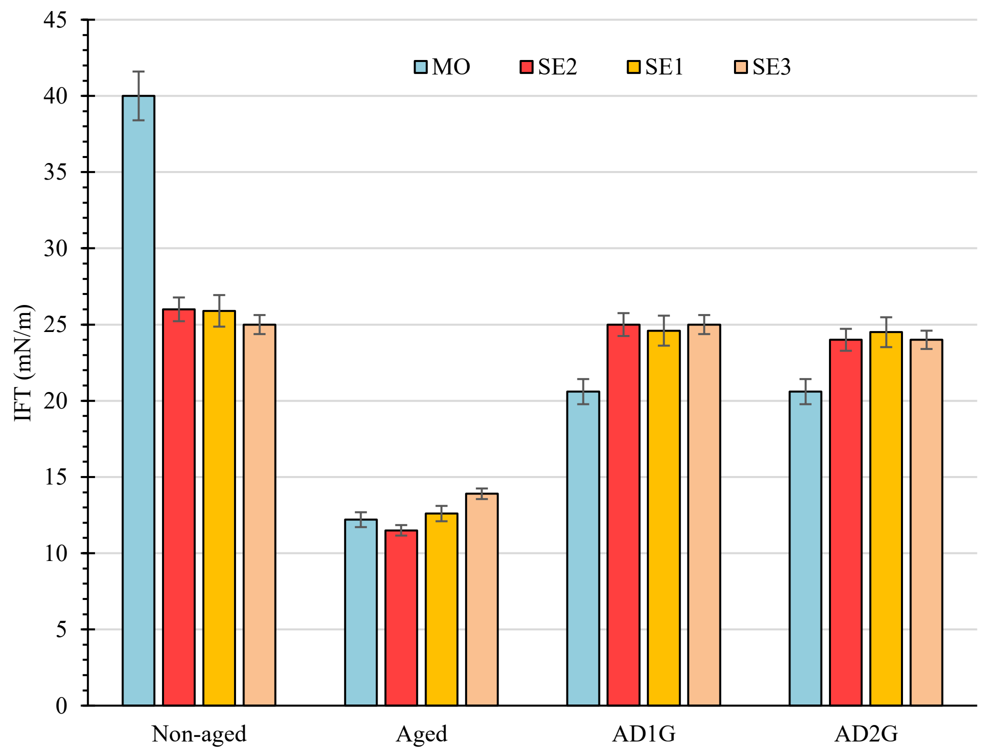
The physicochemical characterizations, including acidity, interfacial tension (IFT), water content, AC breakdown voltage (AC BDV), viscosity at different temperatures, particle count, and Ultraviolet-visible infrared spectroscopy (UV/Vis), are performed on the aged liquids before and after reclamation. It is to be understood that the reclamation is performed only for one cycle (a single pass). The results of the changes in the liquid properties after gravity percolation are presented in this section. In the results, AD1G represents adsorbent 1 with gravity percolation, and AD2G represents adsorbent 2 with gravity percolation. The results reported are the average of three measurements.

2.3.2.1. TOTAL ACID NUMBER AND INTERFACIAL TENSION

Figure II. 4 represents the total acid number and interfacial tension measured before and after the reclamation of MO, SE1, SE2, and SE3 with two adsorbents, AD1 and AD2, under the gravity percolation method. The non-aged samples are also considered for a baseline comparison. It is observed that the acidity of all liquids increases with aging, and it has been reduced with the reclamation process. The acidity of the treated liquid is similar to that of the new liquids in the case of ester liquids, with AD1 and AD2. Also, in the case of mineral oil, the acidity has been reduced but is not as close to the acidity of the new liquid. On the other side, the interfacial tension of the liquids decreased with the aging and is further improved with the reclamation process. This trend has been noticed for all four insulating liquids under consideration. However, in the case of esters, the improved interfacial tension value is close to that of the new liquids. It is to be noted that the acidity and interfacial tension of the reclaimed ester liquids are within the acceptance limits for a new liquid as per the literature and standards [4, 21]. A similar observation has been discussed in the pressure percolation section. It is clear that both AD1 and AD2 are capable of removing the oxidation by-products formed during aging. The oxidation products are trapped in the aged liquid by being either physically or chemically bonded to the active surface of the adsorbents during the treatment process. This retention of the oxidation products by the adsorbent is majorly attributed to the adsorbent saturation (availability of the active surface), to the temperature of the feed liquid, and to the temperature of the adsorbent during the treatment process.



(a) Acidity



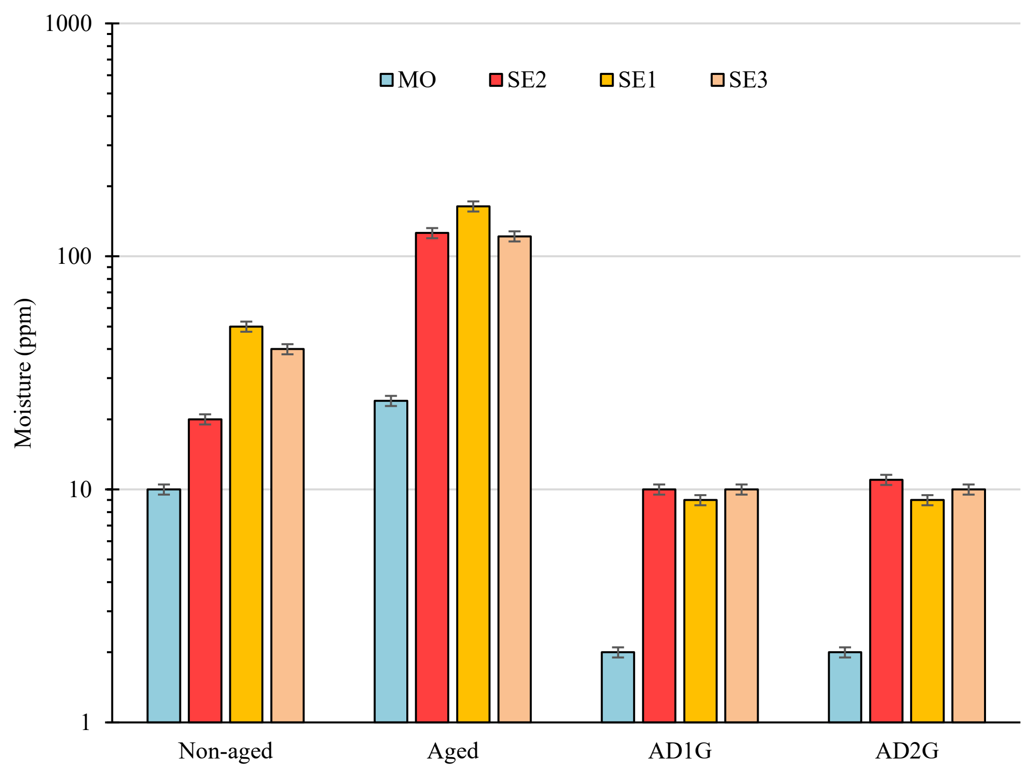
(b) IFT

Figure II. 4. Variations in acidity and interfacial tension of various liquids with reclamation by gravity percolation.

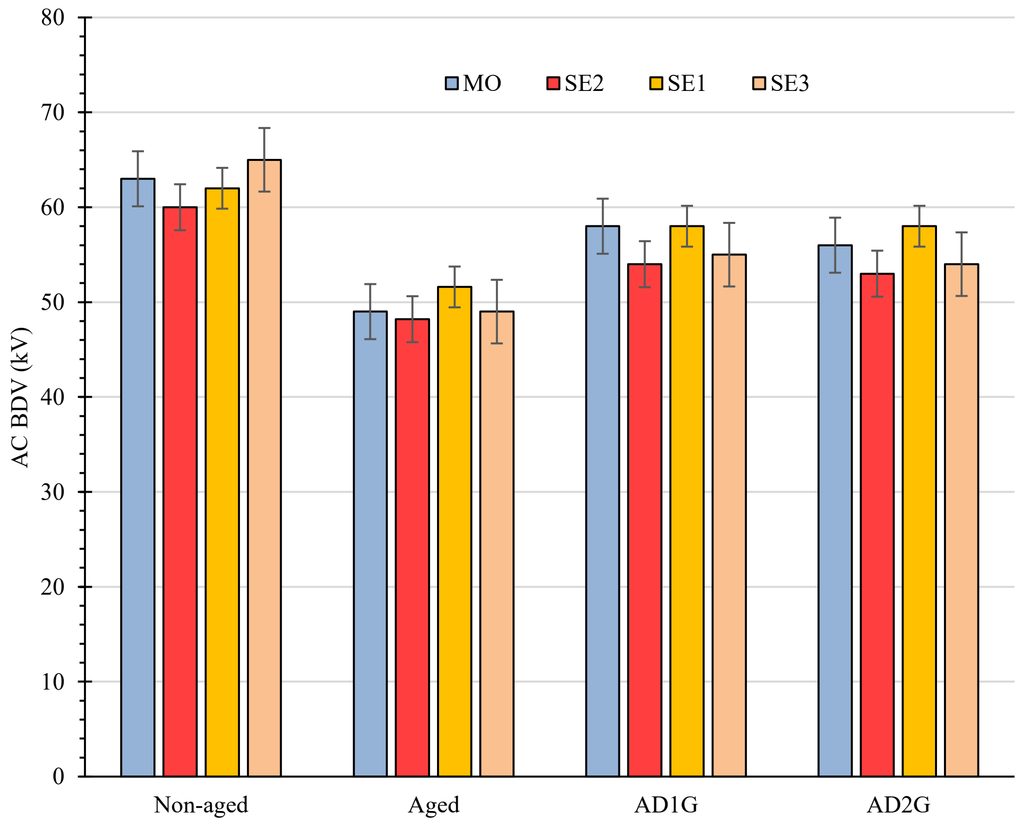
2.3.2.2. MOISTURE AND BREAKDOWN VOLTAGE

After eight weeks of aging, MO has reached 24% of its saturation, while the ester liquids have reached 5–8% of saturation. The saturation limits are reported in [22]. Dehydration of the liquids is performed at 65ºC for mineral oil and 75ºC for esters for 48 hours under vacuum, which is similar to industrial practice following the decontamination of mineral oil. It is important to note that moisture content and AC BDV measurements for the reclaimed liquids are taken after the filtrate has undergone dehydration. Figures II. 5(a) and II. 5(b) represent the moisture in liquids and the breakdown voltage of liquids, respectively. The measurements include before and after the reclamation of MO, SE1, SE2, and SE3 with two adsorbents, AD1 and AD2, under the gravity percolation method. The breakdown voltage values of all four test liquids are improved with the reclamation and are within the acceptable limits, which are 25 kV for MO (regenerated) and 30 kV for synthetic esters (non-aged fluid). This increase may be attributable to the improvement witnessed in the TAN and IFT after reclamation and also taken further by the dehydration process.

Let us recall that the adsorbent is preheated to escape any moisture and also to activate the adsorbent surface. Since the adsorbents are cellulose-based and preheated, the moisture in the liquid may be trapped on the dry surface of the adsorbent during the treatment process. Also, an oil-impregnated filter paper is placed at the outlet of the syringe to restrict any particulates in the filtrate. These factors are responsible for the reduced moisture and the increased breakdown voltage.



(a) Water content



(b) AC BDV

Figure II. 5. Moisture in oil and AC BDV of liquids: Nonaged, Aged, and after reclamation by gravity percolation.

2.3.2.3. KINEMATIC VISCOSITY AT DIFFERENT TEMPERATURES

It is to be recalled that thermal aging is performed under unsealed conditions, with a higher scope for oxidation of the liquids. The oxidation of insulating fluids generates high molecular weight compounds, which in turn increase the oil's viscosity [1, 2]. Therefore, the viscosity of the liquids is measured at different temperatures ranging from -35°C to +20°C. The changes in viscosity of the liquids for non-aged, aged, and reclaimed liquids with AD1G and AD2G are shown in Figure II. 6. The increase in viscosity of the liquids following the 8 weeks of thermal aging is majorly due to oxidative degradation. At low temperatures (less than -20ºC), the viscosity of MO, SE1, SE2, and SE3 is reduced with the reclamation process due to the removal of the polar compounds. However, at 20ºC, the viscosity values of the reclaimed liquids are either reduced and/or comparable to those of the liquid that has been aged for 8 weeks.

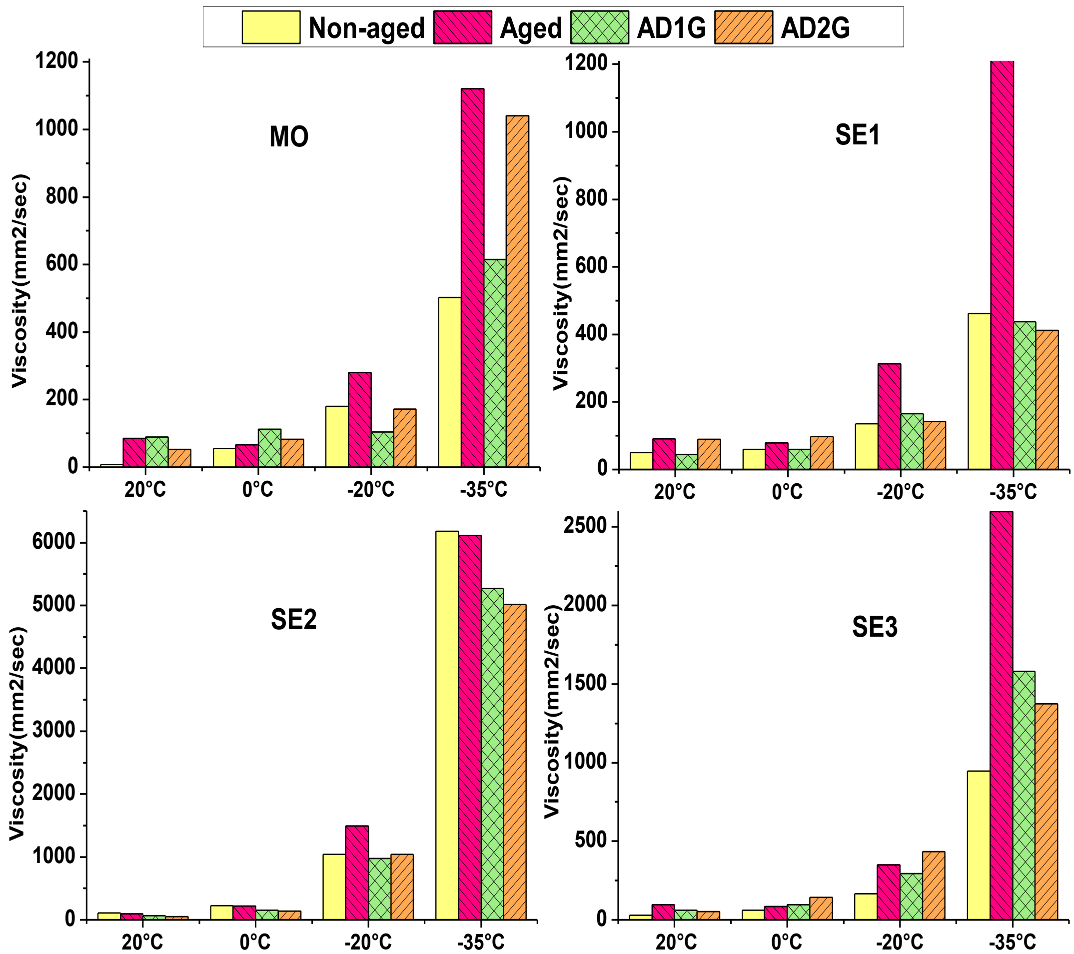
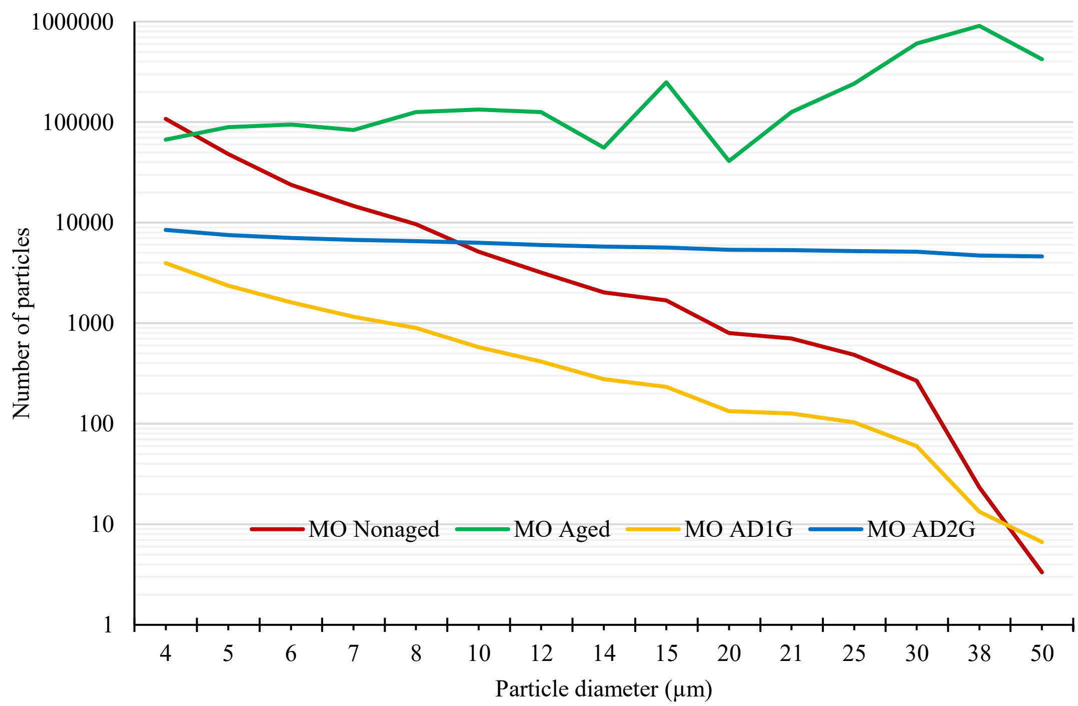


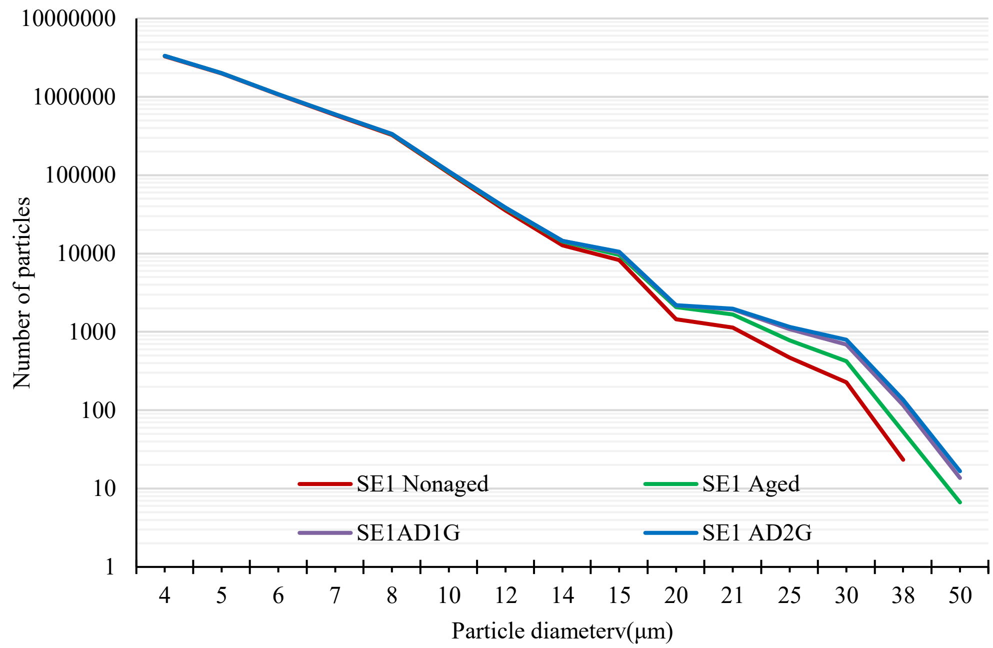
Figure II. 6. Viscosity of liquids before and after reclamation by gravity percolation.

2.3.2.4. PARTICLE COUNT

The particle counter has been used to measure the number of tiny particles present in the liquids (non-aged, aged, and treated). Figure II. 7 presents the number of particles as a function of the particle diameter for MO, SE1, SE2, and SE3. The particles in all the liquids are seen to increase with aging, which is caused by the generation of aging by-products through accelerated thermal aging. The decay content and number of particles are lesser in the case of ester liquids, which aligns with the literature [15]. A significant change in the number of particles with reclamation has been noticed in the case of mineral oil. However, this change is very negligible in the case of all three ester liquids. This is because esters are polar in nature, and most of the polar oxidizing products are dissolved in esters and treated as soluble decay products [15, 23]. As per the CIGRE technical brochure 157 [24], particles less than 25 microns are considered soluble particles in the case of mineral oils. It is to be noted that, in the case of ester liquids, the trend almost overlapped for particle diameters lesser than and equal to 25 microns. On the other side, esters (feed liquid) have higher moisture content and higher fatty acids. These factors may also invite a possible reaction between the ester group and the rough surface of the adsorbents (magnesium silicates) that may introduce further tiny particles during the reclamation process [15]. These soluble particles typically impact the liquid absorbance and turbidity considerably. Additional analysis is required to further comment on the nature and behavior of these particles.

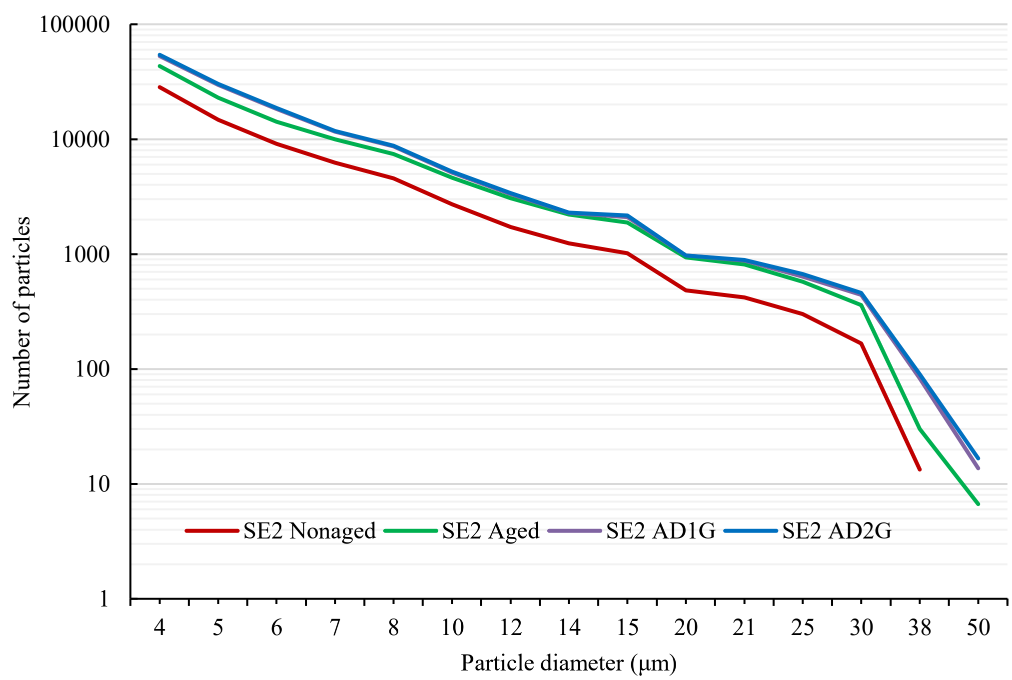


(a) MO



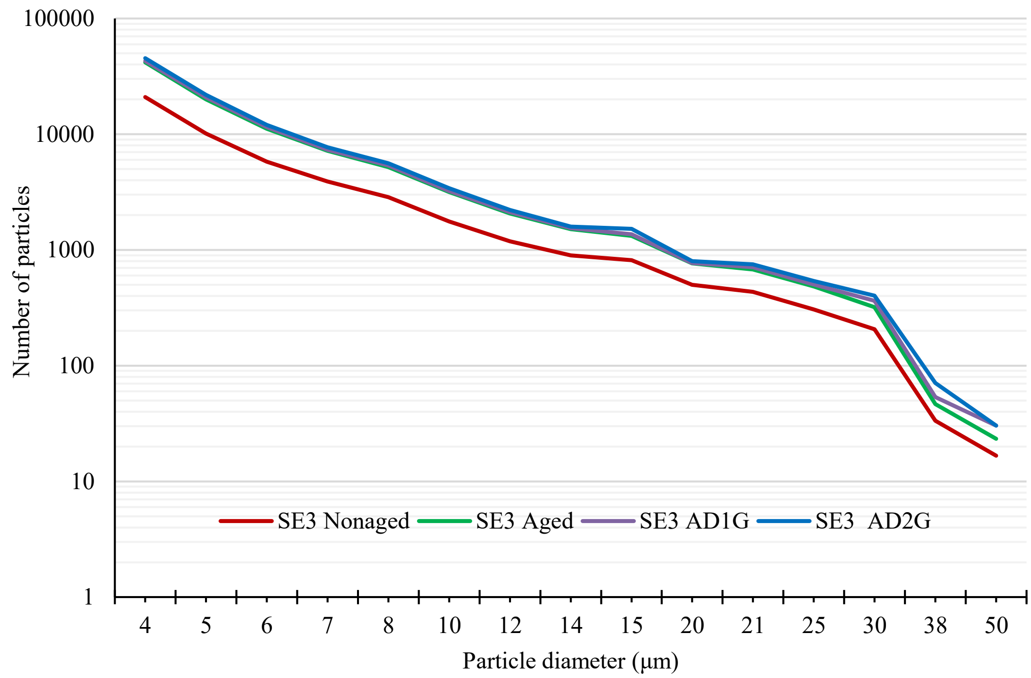
10000000
1000000
100000
10000
1000
100
10
1
Number of particles
SE1 Nonaged
SE1 Aged
SE1AD1G
SE1 AD2G
4
5
6
7
8
10
12
14
15
20
21
25
30
38
50
Particle diameterv(μm)

(b) SE1



100000
10000
1000
100
10
1
Number of particles
SE2 Nonaged
SE2 Aged
SE2 AD1G
SE2 AD2G
4
5
6
7
8
10
12
14
15
20
21
25
30
38
50
Particle diameter (μm)

(c) SE2



(d) SE3

Figure II. 7. Particle count of liquids before and after reclamation by gravity percolation.

2.3.2.5. ULTRAVIOLET-VISIBLE SPECTROSCOPY

Figure II. 8 presents the results of the liquid's (MO, SE1, SE2, and SE3) absorbance to light in ultraviolet and visible regions (UV-Vis spectroscopy). It is noticed that the absorbance is increased with thermal aging and is reduced with the reclamation process but not to the original unaged values. This change in absorbance is due to the removal of aging byproducts during the reclamation process. This could indicate the ability of the chosen adsorbents and the reclamation process to remove, to a certain extent, the colloidal and soluble decay content in the feed liquid. The color of the aged and reclaimed liquids is shown in Figure 9 to support the discussions.

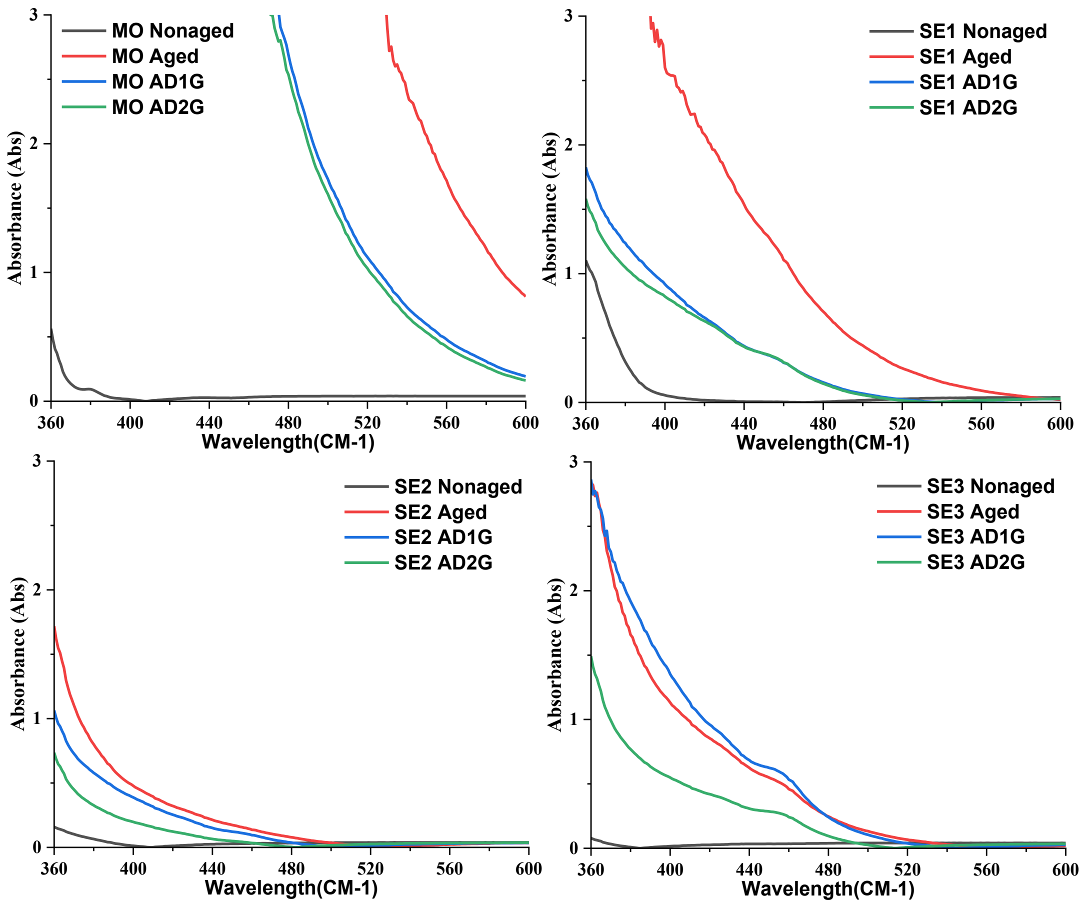


Figure II. 8. UV-Vis absorbance curves of liquids before and after reclamation by gravity percolation.

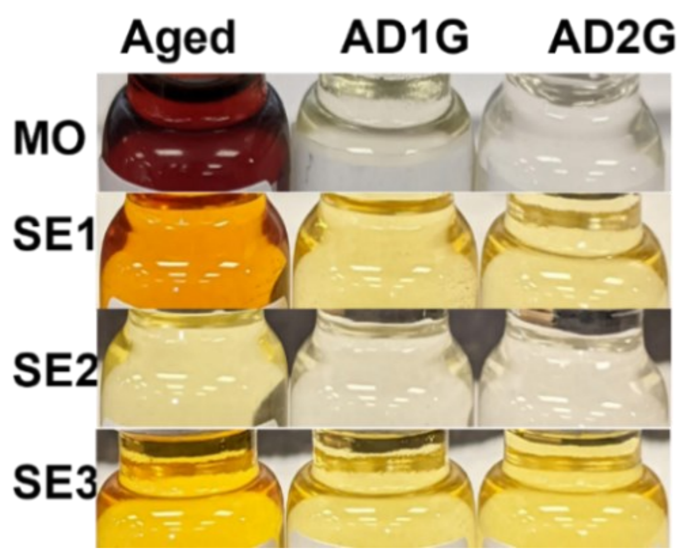


Figure II. 9. Color changes in the liquids with reclamation by gravity percolation.

2.4. CONCLUSION

This article presents experimental evidence on the viability of adsorbent-based reclamation of synthetic ester liquids with a new class of adsorbents. The results also focus on two different percolation methods. Both adsorbents are highly effective at removing soluble polar contaminants and oxidation products from ester fluids. Pressure percolation appears to be challenging due to the high suction pressure exerted by the fine particle size of the adsorbents. Higher water content and a decrease in breakdown voltage was observed.

In contrast, the gravitation percolation method showed improved dielectric breakdown voltage, although samples were pretreated (removal of moisture) before testing. The reduction in viscosity and absorbance (improvement in color) with treatment also supports the conclusion that gravitation percolation provides better results.

However, there is a need to investigate other influencing factors such as the number of passes, the cost of the adsorbents, the ratio of adsorbent to oil, and the conditioning of the oils after reclamation, to explore the feasibility of using these adsorbents at the industrial level.

This study only considers oil aged at 150°C for a period of 8 weeks. Hence, the effects of treatment for longer-aged oils should also be studied.

CHAPTER III

PREBREAKDOWN AND BREAKDOWN BEHAVIOUR OF LOW POUR POINT DIELECTRIC LIQUIDS UNDER NEGATIVE LIGHTNING IMPULSE VOLTAGE

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PREBREAKDOWN AND BREAKDOWN BEHAVIOUR OF LOW POUR POINT DIELECTRIC LIQUIDS UNDER NEGATIVE LIGHTNING IMPULSE VOLTAGE

Abstract

In this paper, some investigations on the prebreakdown and breakdown phenomena of low pour point insulating liquids under negative lightning impulse voltage are reported. The tested liquids include mineral oil, a typical synthetic ester, and two low pour point synthetic esters. These liquids underwent accelerated thermal aging. The non-aged and aged samples were subjected to lightning impulses using a point-plane electrode arrangement. The discussions are focused on the initiation of partial discharges, propagation of streamers, and breakdown behaviour in the non-aged and aged liquids. The investigated parameters include inception voltage, lightning impulse breakdown voltage, streamer acceleration voltage, and streamer velocity. The results are supported by the oscillographs of the light activity that is recorded during the discharge process. The prebreakdown phenomenon noticed in the typical synthetic ester vis-à-vis mineral insulating oil is in line with the existing literature. Importantly, it is noticed that the inception and breakdown voltages of the non-aged low pour point synthetic esters are similar to non-aged mineral oil. In addition, the inception and breakdown voltages of the aged low pour point synthetic esters are noticed to be higher than that of the aged mineral oil. These results add to the arguments in favor of replacing mineral oils in power transformers.

3.1. INTRODUCTION

Alternatives to mineral insulating liquids for power transformer insulation systems is a tremendous topic of research in the global power transformer industries. Indeed, the wide acceptance of ester dielectric fluids in power transformers, along with the application of esters in cold countries, is a challenging research topic [1]. Esters, for use in cold regions is least emphasized in the existing literature and is a topic of high interest to the transformer communities. One of the major factors that make esters a questionable and dilemmatic candidate for cold climatic regions is their affinity to moisture. Under fast-reducing temperature transients, the water relative saturation limit reduces drastically [1]. This means that the ability of esters to hold water will be much less at low temperatures, providing the possibility to have freely available water molecules within the bulk volume of the liquid, subsequently leading to the evidential formation of ice crystals in the transformer tank. It is to be recalled that the density of esters is close to the density of the water. This means that the ice crystals formed at low temperatures may be floating in the tank, at least not settled down to the bottom of the tank [2]. Such a situation may critically endanger the insulation system. Apart from the water saturation limit, the temperature has a potential impact on the dielectric properties and other behavioral aspects of the insulating liquids [3, 4]. This, thereof, leaves the use of esters for transformers in the northern regions as a continuous challenge to the engineers and electric utility companies.

Lately, low pour point ester liquids have been an important topic for manufacturers and transformer owners [1]. Unfortunately, very limited literature is available. It is important to understand the workability of the low pour point ester liquids in comparison with the commercially available typical ester liquids to scale these new liquids with the existing literature and industry standards.

The prebreakdown phenomena of transformer liquids have always been an interesting topic for electrical and dielectric engineers [4, 5]. A piece of sound knowledge on the development and behaviour of streamers within the insulation system is important for dielectric design with effective safety margins. To date, numerous studies have been reported on understanding the initiation of streamers in the case of mineral oil and ester liquids [1, 5, 6]. Also, the propagation of streamers is reported in terms of propagation modes, acceleration voltage, streamer velocity, and stopping lengths [6]. The development of discharges, propagation of streamers, and breakdown are usually evidenced by luminous effects. Therefore, various researchers have focused on understanding the prebreakdown phenomena based on photographic and other optical approaches [7]. A large portion of the literature includes a comparative analysis of esters (both natural and synthetic) and mineral oils. It is inferred that esters offer a lower resistance to ionization than mineral oils [1].

The prebreakdown phenomena of dielectric liquids is majorly attributable to the type/magnitude of the voltage, electrode geometry, and stress duration [6]. A few other parameters like temperature, degree of contamination, and type of liquid also have a potential influence on streamer behaviour [6]. The authors' group has reported the influence of aging and the needle tip radius (point-plane) for a newly developed low pour point synthetic ester in comparison with mineral oil under AC stress [8]. The breakdown behaviour of transformer liquids under the lightning impulses always has special importance since transformers in service are prone to lightning discharges and surge strikes. As per Beroual et al. [9], most of the lightning discharges in the northern hemisphere of the earth are of negative polarity. Various researchers studied the streamer behavior under negative and positive lightning impulses for esters and mineral oil [10]. It is widely reported that the dielectric performance of mineral oil under lightning impulse is better than that of ester dielectric liquids [6]. Therefore, in this work, a typical synthetic ester and mineral oil are included along with two low pour point synthetic ester liquids with the aim of comparing their behavior.

The fluids are subjected to standard lightning impulses of negative polarity under point-plane configuration. For better understanding, non-aged and aged liquids are considered for the experimental analysis. The test liquids are analyzed based on the streamer parameters, including streamer inception voltage, acceleration voltage, streamer velocity, and lightning impulse breakdown voltage. The analysis is based on the oscillographs recorded for the changes in the voltage and associated light activity during the inception, propagation, and breakdown activities.

3.2. EXPERIMENTAL

3.2.1. THERMAL AGING

Mineral oil (MO), two low pour point synthetic ester liquids (SE1 and SE2), and a typical synthetic ester (TSE) are subjected to accelerated thermal aging. The thermal aging procedure follows a modified ASTM D1934–20 procedure [11]. The aging is performed in open beakers (borosilicate glass) in a conventional mechanical oven at 150 °C for 8 weeks. To induce a significant degradation of liquids and simulate a transformer insulation system, cellulose kraft papers are introduced to aging beakers with a paper-to-liquid weight ratio of 1:20. A 24 hours cooling period is adopted after thermal aging to allow appropriate partition time for the decay products between liquid and paper samples.

3.2.2. PHYSICOCHEMICAL TESTS

Some physiochemical characterizations were performed for fresh and aged liquids (without any treatment) to understand the level of degradation. These characterizations include interfacial tension (IFT), total acid number (TAN), density, viscosity, breakdown voltage (AC BDV), and moisture. This allowed having a total of eight liquid samples (four non-aged and four thermally aged) for negative lightning impulse voltage testing. The aged liquids are considered as test liquids without any additional treatments. The properties of liquids representing non-aged (N) and aged (A) for the test liquids are tabulated in Table III. I.

TABLE III. 1. Characteristics of the test liquids

Parameter	Units	Insulating liquids used for testing							
		MON	MOA	SE1N	SE1A	TSEN	TSEA	SE2N	SE2A
IFT	(mN/m)	40	12.2	26	12	26	13	25	14
TAN	(mgKOH/g)	0.01	0.09	0.01	0.15	0.01	0.18	0.01	0.14
Density	Kg/m^3	0.88	0.86	0.91	0.91	0.97	0.97	0.95	0.94
Viscosity	(cSt)	7.5	86	50	90.5	110	96	30	95.5
AC BDV	(kV)	63	49	60	46	62	45	65	47
Moisture	(ppm)	10	24	20	126	50	164	40	122

3.2.3. MEASUREMENT SYSTEM AND ELECTRODE CONFIGURATION

For the present study, a point-plane electrode configuration has been used with a tungsten needle (high-voltage electrode) having a tip radius of 50 µm and a copper plane (grounded electrode) of 3.5 cm diameter with an inter-electrode gap of 30 mm. Point-plane electrode system studies have been widely accepted for the experimental analysis of transformer liquids. This is best suited for any practical diagnostic based on partial discharge [6]. The high-voltage needle electrode has been supplied with a source voltage by using a six-stage Marx generator (500 kV) with a stored energy of 2.2 kJ. The voltage supplied to the high-voltage electrode is a standard lightning impulse (LI) voltage, 1.2/50 µs. A peak voltage meter (PVM) and resistive voltage divider with a voltage ratio equal to 1000 are deployed for measuring the applied voltage. To record the test waveforms, a digital oscilloscope (OSC) with a sampling rate of up to 2.5 Gs/s and 500 MHz bandwidth is adopted. For the light activity registration, an optical cable with a photomultiplier tube (PMT) operating at a wavelength range of 300 to 850 nm is used. One end of the PMT cable is positioned close to the electrode gap through the transparent test cell, while the other end is connected through the dedicated amplifier to the OSC. The high-voltage generator and the measuring system, along with the test cell used for lightning impulse testing of the test liquids, is shown in Figure III. 1.

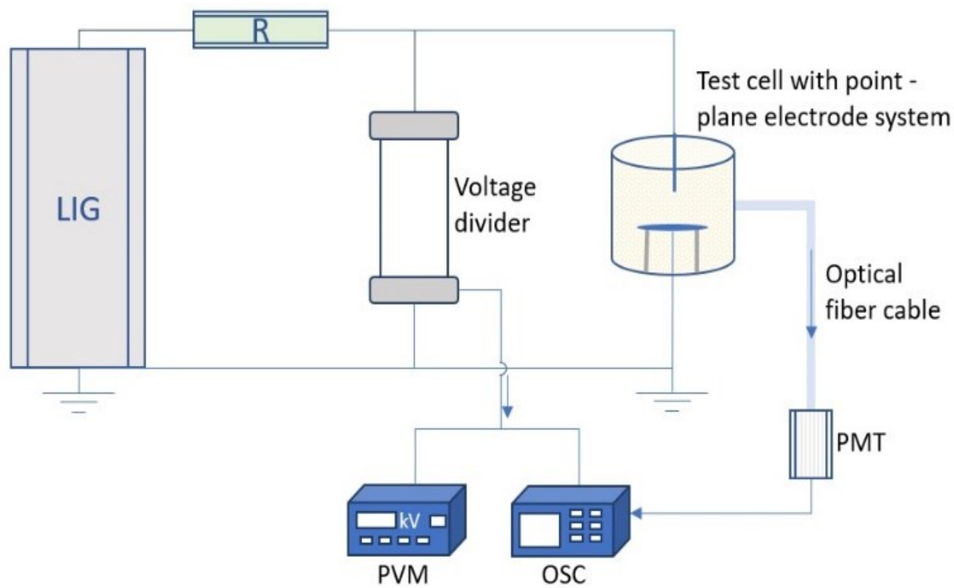


Figure III. 1. Measurement setup used for testing: LIG – lightning impulse generator, R – current limiting resistor, OSC – digital oscilloscope, PMT - photomultiplier tube, PVM – peak value meter.

3.2.4. MEASURING PROCEDURE

The IEC 60897 testing procedure is followed for testing the liquid samples. The subsequent lightning impulse supplied to the point-plane electrode system is assumed to be U=5 kV, which is supplied with a time gap of t=1 minute, as per IEC 60897. The supply of the lightning impulses with a subsequent increase in 5 kV and one minute delay is continued until a lightning impulse breakdown (LIBV) occurs across the gap, referred to as one series of measurements. As per IEC 60897, a minimum of 5 LIBV series is required to access the average LIBV of a liquid. In the present study, ten LIBV series measurements are performed with a liquid relaxing time, T= 5 minutes between series. The testing sequence is shown in Figure III. 2.

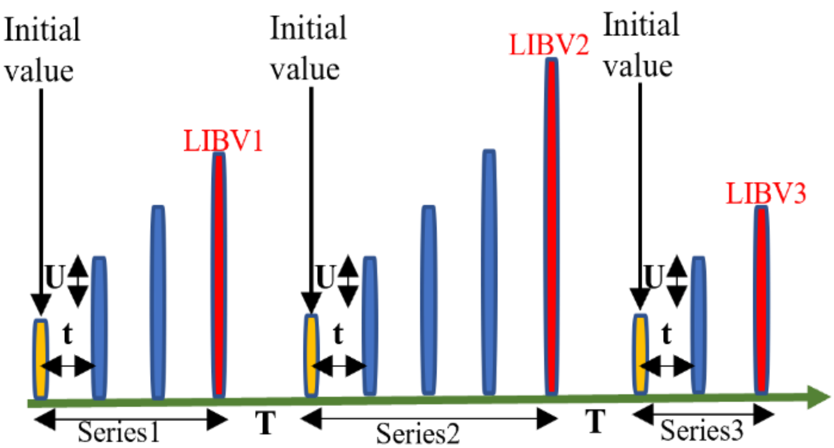


Figure III. 2. The procedure adopted for LIBV measurement: LIBV1, LIBV2, LIBV3 – subsequent breakdown voltages, U – assumed voltage step, t – time lag between the subsequent LIs, T – time delay between measurement series.

After every five series of measurements, the needle is replaced with a new one, and the electrode gap is verified. This is because the breakdown and the shockwaves influence the tip radius; thus, the consistency in the tip radius is maintained by changing it to a new one. The breakdown is evident by a strong physical and discharge activity called a streamer. The PMT records the light activity, which is used to understand the behavior and/or nature of the streamer. Due to significant differences in the range of the voltage magnitudes for different parameters like inception and breakdown, different source voltage configurations are adopted. The details are discussed below.

For Inception Voltage: Inception voltage is the voltage at which the onset of the streamer is recorded by the light activity. Thus, the value is much lower than that of the typical breakdown voltage. Thus, a two-stage Marx generator with the above-discussed configuration is adopted with a starting voltage of 45 kV with a negative polarity. A set of five measurements have been performed on each liquid, and the average values are used for analytical purposes.

For Breakdown Voltage: Since the breakdown voltages are generally on the higher side, the starting voltage of the generator has been set to 75 kV with a negative polarity. A six-stage Marx generator configuration is deployed for breakdown voltage measurements. The test sequence is followed as explained earlier (see Figure 2).

For Acceleration Voltage: To measure the acceleration voltage, a six-stage Marx generator configuration is deployed. The starting voltage depends on the tested liquid. The average lightning impulse breakdown voltages of individual liquids are used as starting voltages for acceleration voltage measurements. This is important to avoid degrading the liquids with unwanted impulses (repeating from lower values) while also reducing the testing time.

3.3. RESULTS AND DISCUSSIONS

3.3.1. STREAMER INCEPTION VOLTAGE

It is very important for an insulating liquid to offer sound resistance to the ionization in the bulk of the liquid. The critical electrical stress, where ionization of the liquid starts, is generally referred to as the inception voltage [8]. In general, the inception voltage is an estimate of the onset of partial discharges. However, apart from liquid resistance, the impurities present in the liquid also accelerate the ionization onset of the liquid. Since insulation aging is witnessed by decay particles that act as impurities, it is important to determine the inception voltage in the case of aged liquids as well. Thus, in this work, the inception voltage is investigated for the non-aged and aged liquids. The average inception voltages for non-aged and aged test liquids are summarized in Figure III. 3.

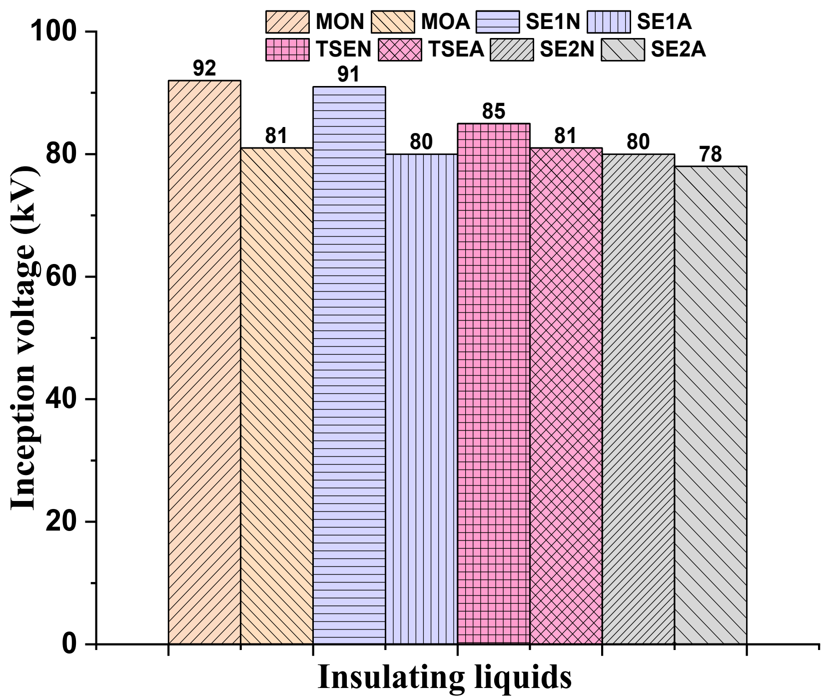


Figure III. 3. Average streamer inception voltages for different test liquids under lightning impulses of negative polarity.

It is observed that the inception voltage of mineral insulating oil is higher than that of the typical synthetic ester in the case of non-aged liquids, while the aged liquids are comparable. This observation is similar to the previous studies reported in the literature [6]. It is noticed that the low pour point liquid, SE1 has a comparable inception voltage with that of the mineral oil, both in the non-aged and aged conditions. This may be because of the difference in the micro molecular structures of the liquids that have influenced the macro-level performance. At the same time, the SE2 is found to have a lower ionization resistance to streamer initiation amongst all the tested liquids. As expected, the inception voltages are less in the case of aged liquids. This is because the presence of decay particles (witnessed by reduced IFT) in the aged liquids act as local conducting particles, which initiate the ionization process at a lower electric field intensity.

3.3.2. BREAKDOWN VOLTAGE

Lightning impulse breakdown analysis is generally useful for insulation design engineers to estimate the withstanding ability of the insulation system under lighting conditions. Typically, negative polarity is considered for prebreakdown analysis because streamers are slow propagating in nature and hence can be analyzed easily. In the present work, a negative polarity LIBV test has been performed on all the test liquids. The average LIBV values are shown in Figure III. 4.

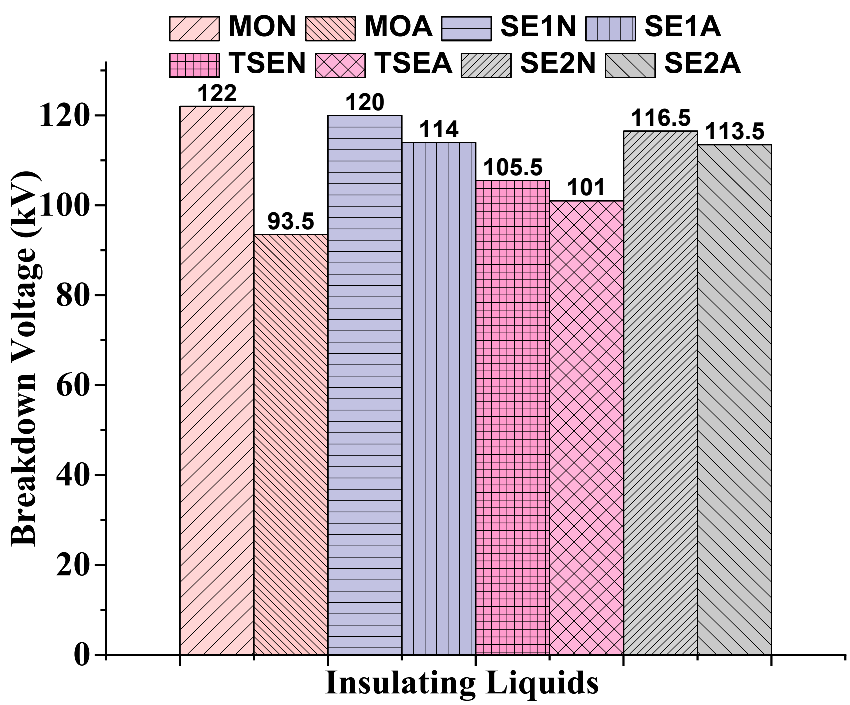
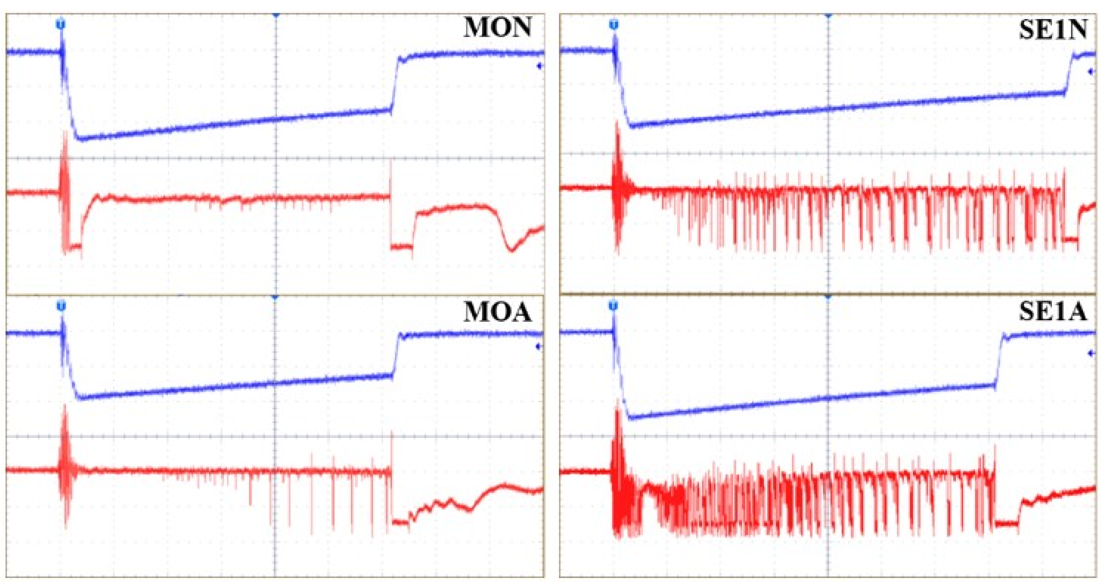


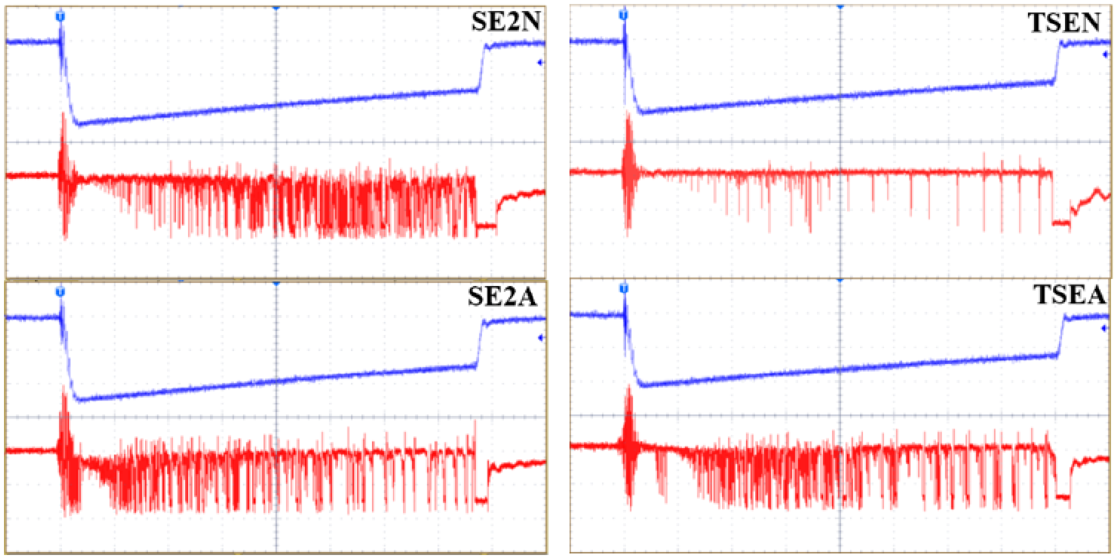
Figure III. 4. Average lightning impulse breakdown voltage for different test liquids under negative polarity.

The LIBV of a typical synthetic ester is observed to be lower than that of mineral-insulating oil; the same is reported by various researchers [6]. However, the change in LIBV with the thermal degradation of liquids is much greater in the case of mineral oil. In the case of ester liquids, a much smaller drop in LIBV is observed with thermal degradation. This may be attributed to the high thermal stability (low rate of degradation) of esters than that of the mineral oil [1]. Also, degradation in mineral oil is typically witnessed by a huge concentration of colloidal particles (mostly cellulose) [8]. However, decay particles are mostly conducting in nature and get polarized easily under the influence of an electric field. Therefore, when the liquid is subjected to a high voltage, the polarized particles tend to accommodate the high field stress regions in the bulk volume of the liquid. In the present experimental conditions, the polarized particles move toward the tip of the high-voltage needle tip and continue to develop a weak link chain between the electrodes. This leads to the phenomenal development of partial discharges or complete breakdown of the liquid [12, 13]. It is also found that low pour-point synthetic ester liquids have better LIBV performance than that of the typical synthetic ester in the case of non-aged and aged liquids. Understanding the MO Vis-à-Vis SE1 and SE2, the non-aged cases are almost comparable, while the aged cases are found better with the low pour point liquids.

The oscillograms of the voltage and the light activity are registered for every lightning impulse supplied to the high-voltage needle electrode to assess the intensity of the processes preceding the breakdown. For illustration purposes, an event of a breakdown and the light activity registered during the streamer propagation for each test liquid are shown in Figure III. 5.



(a) Mineral oil (b) Synthetic ester-1



(c) Synthetic ester-2 (d) Typical synthetic ester

Figure III. 5. Oscillograms registered in the event of breakdown-Voltage and light activity during the discharge process in various test liquids at the negative polarity of LI voltage, t = 4 µs/div., V = 50 kV/div.

The light activity and the intensity of light are totally related to the phenomenal ionization process during the discharge progression [14]. It is to be noticed that the intensity of light emitted by streamers is higher in the case of ester liquids, and also, the frequency of the light pulses appeared to be increased for the case of aged liquids. The higher light intensity in ester liquids is due to differences in the chemical structure of esters and mineral oil. The molecules in the ester group are polar in nature and possess a lower ionization potential than that of the hydrocarbon group, mineral oil [10, 15]. The difference in the frequency of light pulses may be due to the difference in the absorption coefficients of the tested liquids [7]. However, to conclude the same, further in-depth studies are to be pipelined in this direction of analysis.

The Weibull distribution function is widely accepted for the statistical analysis of breakdown voltage values in transformer liquids, both in the case of AC and LI voltages [5, 6, 15, 18]. Therefore, the same is performed with a confidence interval of 95% on the ten LIVB test values of all the test liquids. The 1%, 50%, and 90% breakdown probabilities are computed and tabulated in Table Figure III.2, while the probability distributions are shown in Figure III. 6 and Figure III. 7, respectively, for non-aged and aged liquids.

TABLE III.2. Details Of Lightning Impulse Breakdown Voltage of The Test Liquids

Name	LIBV (kV)	1% (kV)	50% (kV)	90% (kV)
MON	122	103.7	122.7	128.7
MOA	93.5	76.83	94.34	99.97
SE1N	120	108.5	120.5	124.2
SE1A	114	98.3	114.7	119.8
TSEN	105.5	95.1	105.8	109.0
TSEA	101	83.13	101.7	107.8
SE2N	116.5	101.2	117.6	122.7
SE2A	113.5	100.9	114.0	118.0

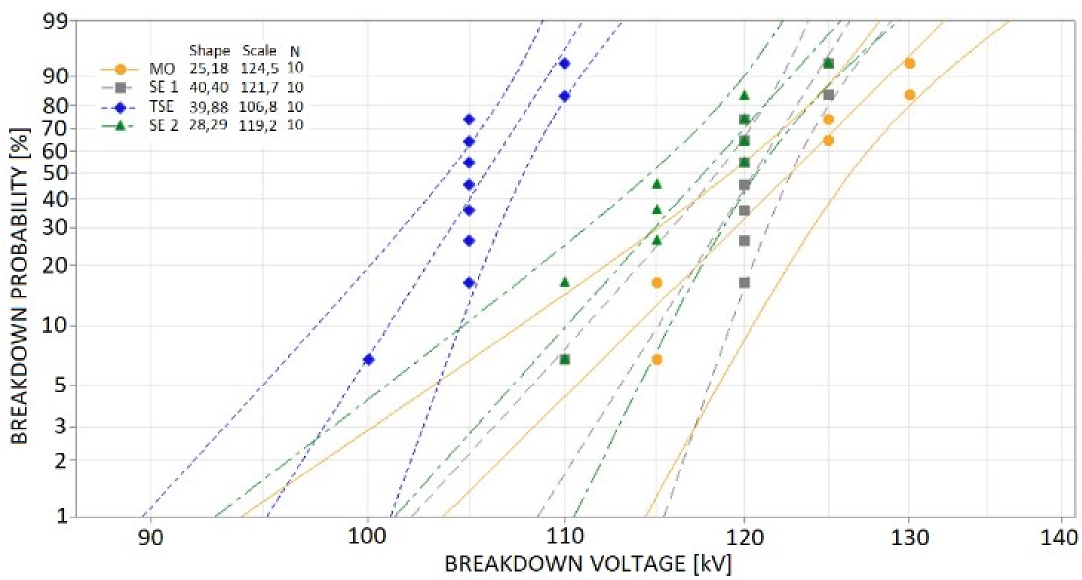


Figure III. 6. Weibull distribution curves of the LIBV of the non-aged test liquids for point plane electrode system under negative polarity.

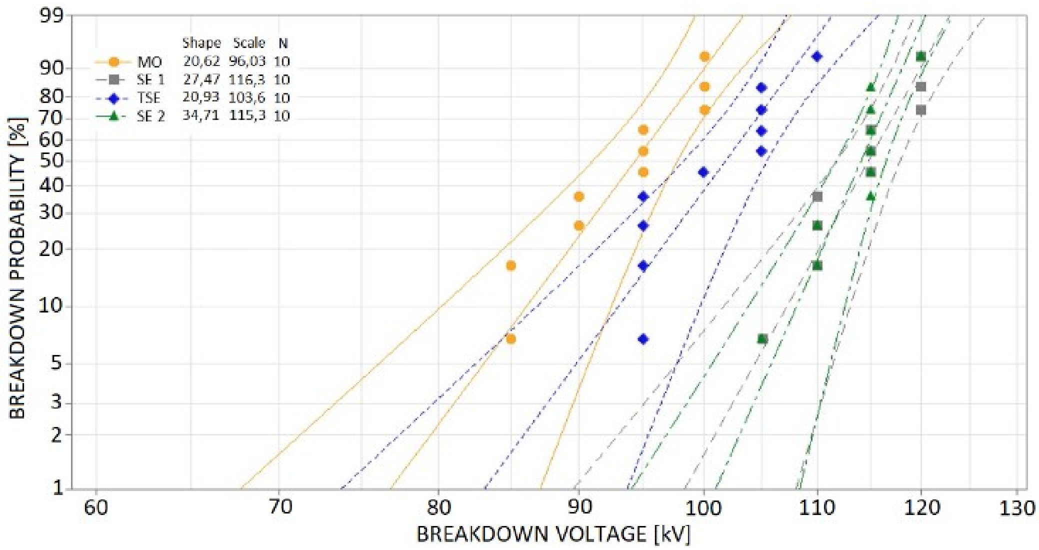


Figure III. 7. Weibull distribution curves of the LIBV of the aged test liquids for point plane electrode system under negative polarity.

As can be seen from the presented Weibull curves, the general relationships between the liquids, which were noticed for average values, are valid also for low breakdown probabilities (mainly 1% breakdown probability is considered as the value used commonly when assessing design safety levels of transformer insulating structure). When comparing the results concerning aged liquids, it can be seen that SE1 and SE2 have the best lightning performance with a marginal higher 1% breakdown probability for SE2. In turn, when comparing non-aged liquids, SE1 has the highest 1% breakdown probability, and MO has a slightly higher average LIBV. A physical explanation of the differences between the liquids presented above correlates with the results of Weibull distribution based analysis.

3.3.3. STREAMER ACCELERATION VOLTAGE

Acceleration voltage is a behavioral factor of the developing streamers that is based on the propagation speed. There is no standard or established definition for streamers acceleration voltage. However, the experience from the literature indicates that the voltage at which the streamers velocity increases significantly is referred to as the acceleration voltage

[6, 16, 17]. A few researchers reported that it is the voltage at which the streamers velocity changed from the 1st and 2nd modes (slow propagating) to the 3rd and 4th modes (fast propagating). An example of voltage and lightning activity indicating the reduction in time to breakdown is depicted in Figure III. 8.

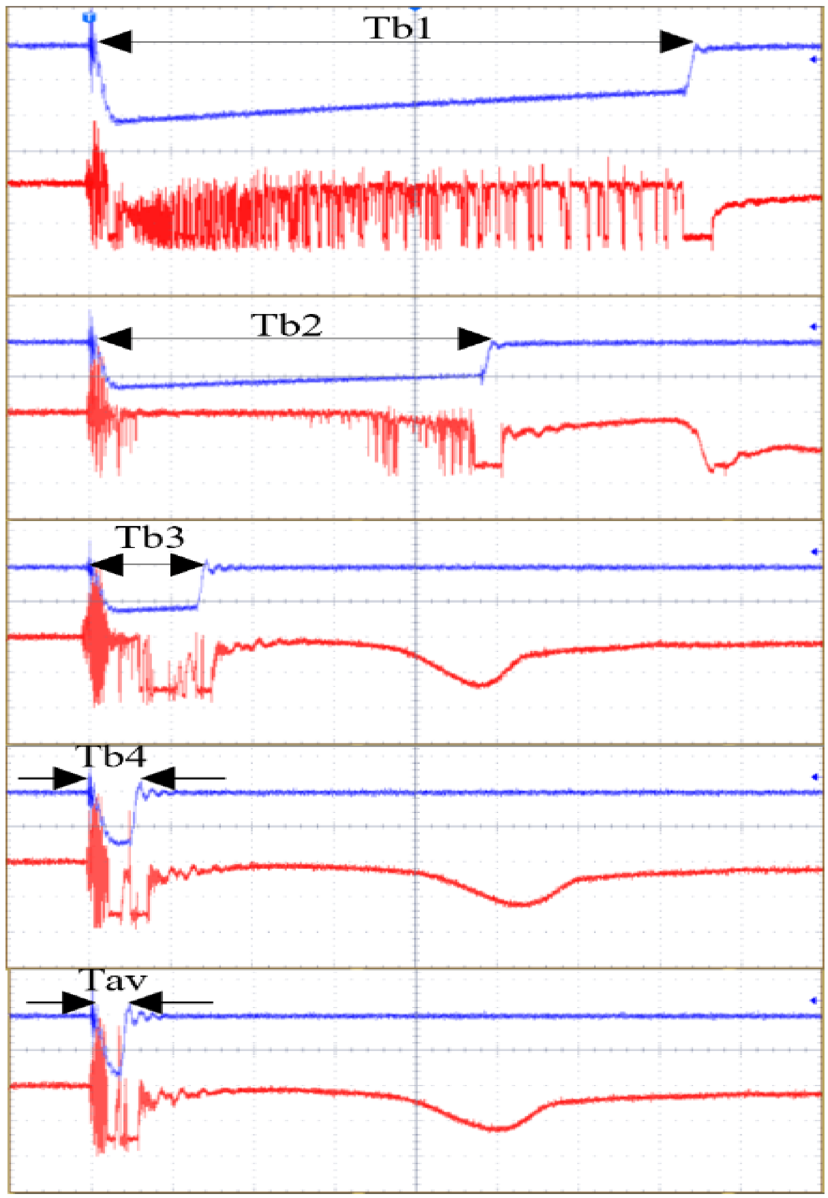
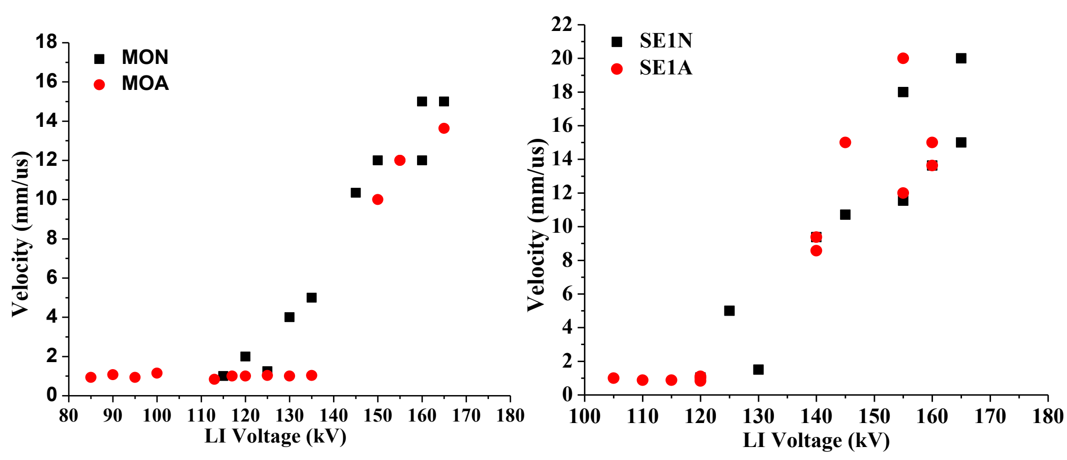


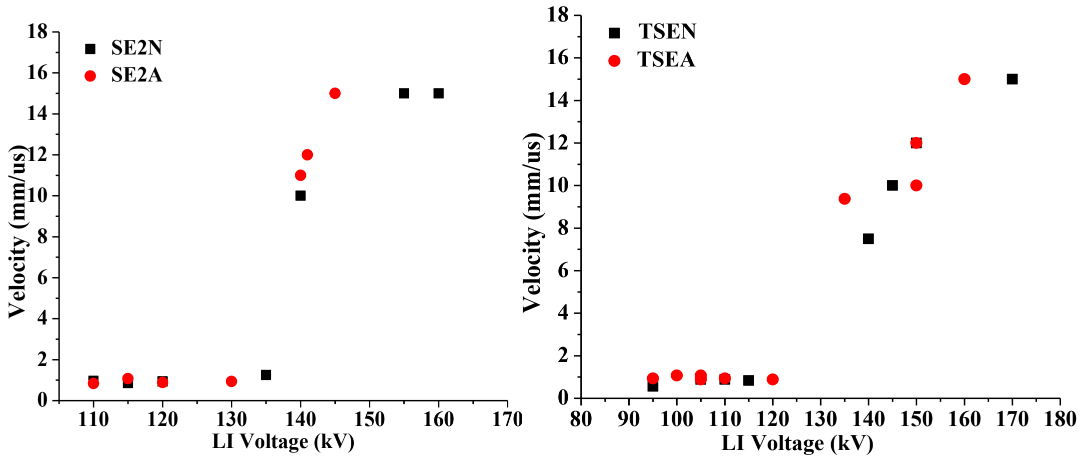
Figure III. 8. Illustration of an example of the oscillograms recorded during the measurements performed for acceleration voltage: Tb1 - average LIBV of the test liquid; Tb2, Tb3, and Tb4 - subsequently reduced time to breakdown with increasing voltage, Tav - time to breakdown < 2 μs corresponding with the acceleration voltage, t = 4 μs/div., V = 50 kV/div.

It is to be mentioned that acceleration voltage means high streamer velocities, therefore, indicating lesser time to breakdown. Also, from the authors' experience, it is noticed that the acceleration voltages are higher than the breakdown voltages in most cases of transformer liquids; the same is reported in [18]. Therefore, the starting voltage is considered the average breakdown voltage of individual liquids. The acceleration voltage measurements are performed by considering the time to breakdown as a reference. The impulses with an increasing voltage higher than the average breakdown are applied until the time to breakdown falls to less than 2 μs. The time to breakdown in Fig. 8 is indicated as Tb1, Tb2, Tb3, Tb4, and Tav. In the 5th oscillograph, the time (Tav) is less than 2 μs, and hence the testing is terminated at this point of time. Later, knowing the distance between the electrodes, the times (time to breakdown) are used to compute the velocities.

Since the streamers acceleration voltage is based on the estimate of propagation velocity, the voltage-velocity curves are developed for all the tested liquids, shown in Figure III. 9. To clearly demonstrate the rise in velocity, a few records from the breakdown measurements have been also considered for the voltage-velocity curves.



(a) Mineral oil (b) Synthetic ester-1



(c) Synthetic ester-2 (d) Typical synthetic ester

Figure III. 9. Streamer velocity as a function of the lightning impulse breakdown voltage (negative polarity), indicating a rapid increase in the streamer propagation after a certain level of voltages.

From the above voltage-velocity plots, the variation in streamers velocity as a function of the applied voltage is understood. It is commonly noted in all the tested liquids that the velocity of the streamers corresponding with breakdown is initially not changed significantly. However, with an increase in the voltage, the propagation velocity increases slowly (slow propagating), and a sudden rise in velocity is evident from a given voltage level. This sudden rise is due to the fact that streamers' propagation mode changed from slow to a fast mode. This transition is dependent on various factors, including the electric field intensity, duration of stress, and type of liquid. It is observed that, in most cases, during the streamers transition from 1st and 2nd modes to 3rd and 4th modes, the propagation velocity is around 10 mm/µs. A similar observation has been reported by various researchers [18]. In general, fast propagating streamers are more detrimental than slow propagating streamers. Hence the acceleration voltage may be helpful for the insulation design engineers to have an estimate of the dielectric safety limits. The voltage at which a sudden rise in velocity is observed is considered as the acceleration voltage. The acceleration voltages and the corresponding velocities for different test liquids are plotted in Figure III.10.

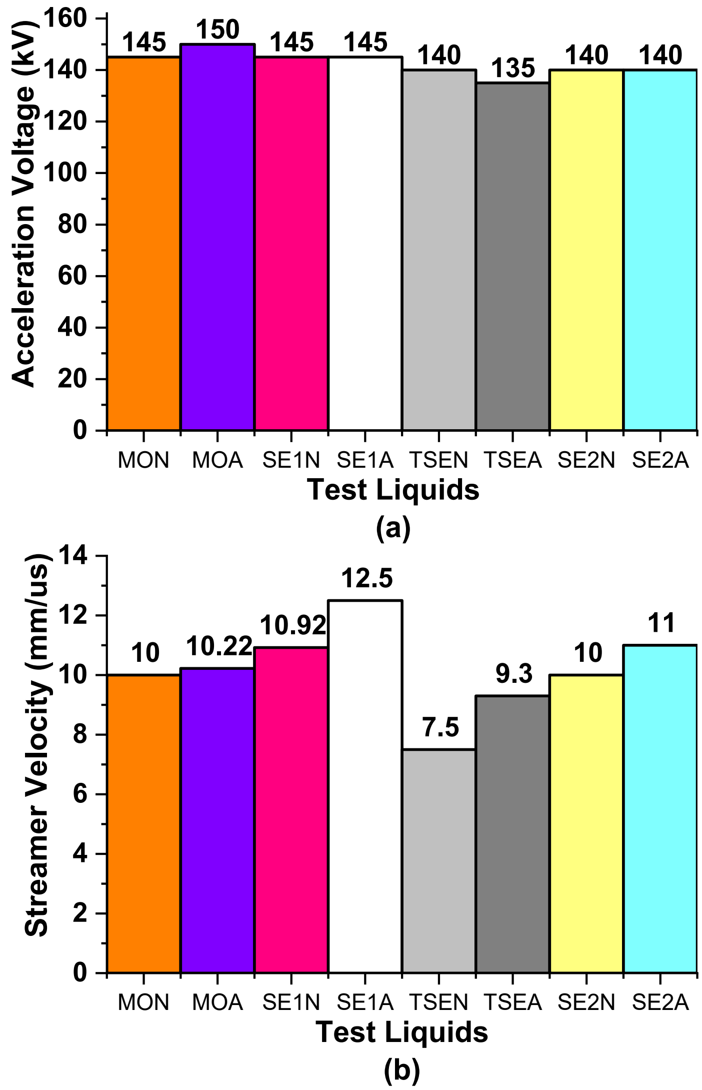


Figure III. 10. Acceleration voltage and corresponding streamer velocities for all the test liquids.

From Fig. 10a, it is observed that the liquid deterioration has no significant impact on the acceleration voltage. Theoretically, owing to the decay products, liquid degradation is expected to have a significant impact on the liquid breakdown voltage; the same is observed in the LIBV results discussed in the previous section. It is to be noted that the acceleration voltage is much higher than the breakdown voltage in the case of all the test liquids, thus indicating a much higher magnitude of the electric stress imposed by the source on the needle electrode (immersed in the liquid volume). It is to be recalled that at a very high electric field intensity, there is a high possibility for the existence of space charges. According to the Fowler Nordheim effect, space charges may be evolved on the surface of the conductors (needle electrode) and may be injected as individual electrons into the bulk of the liquid [19]. Also, as per the Schottky effect, the work function (supplied by heat generated at the needle tip) is reduced at high electric fields [20], thus reducing the energy required for electron emission from the needle tip. In addition to these effects, the ionization of liquid is much higher at higher electric filed, and the transport time for the charges is drastically reduced. It is also to be remembered that the electrode configuration in the present study is point-plane, and hence the gap space charges develop easily due to the local field and influence the rate of electron inception. Therefore, the impact of the space charges may be considered in support of the acceleration voltage results, with no difference between the aged and non-aged liquids while having a similar range for all the test liquids. This hypothesis may be accepted with an assumption that due to a high field stress buildup, the space charges injected by the high-voltage electrode have taken the lead of the streamer buildup process. In addition, it should be noted that according to existing knowledge, the liquid molecules are directly involved in the propagation of fast streamers. Thus, the impurities, bubbles or liquid decomposition byproducts due to aging do not influence the fast streamers generation. From this statement, it is easy to explain why there are no differences between acceleration voltage of non-aged and aged liquids. However, the propagation velocities (see Fig. 10b) corresponding to the acceleration voltage are higher in the case of aged test liquids. The decay particles, being typically conductive in nature, tend to aid the streamers' growth, also in case of fast mode propagations.

3.4. CONCLUSION

The following conclusions may be drawn based on the measurements conducted:

The inception voltages for aged liquids are lower than that of the non-aged liquids. This is due to the presence of decay particles in the volume of aged liquids, which act as local conducting particles and involve streamer initiation at a lower electric field intensity.

The pre-breakdown and breakdown behaviour of non-aged SE1 and SE2 are noticed to be higher than that of the aged mineral oil. This may be attributable to the difference in the micro molecular structures of the liquids that have affected the macro-level performance.

The breakdown behaviour of aged TSE is better than that of aged mineral oil. However, the aged low pour point synthetic esters are relatively much better than TSE.

LIBV is also reduced with thermal aging regardless of the type of liquid. However, this influence (reduction), is higher in the case of mineral oil.

Thermal aging process has not influenced the acceleration voltage under the present experimental condition (non-uniform field and smaller gap distance). However, the generalization of this statement requires similar studies for longer gaps.

CHAPTER IV

ANALYSIS OF BREAKDOWN VOLTAGE OF LOW POUR POINT SYNTHETIC ESTER INSULATING LIQUIDS UNDER LIGHTNING IMPULSE VOLTAGE OF BOTH POLARITIES

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ANALYSIS OF BREAKDOWN VOLTAGE OF LOW POUR POINT SYNTHETIC ESTER INSULATING LIQUIDS UNDER LIGHTNING IMPULSE VOLTAGE OF BOTH POLARITIES

Abstract

In this article, lightning impulse breakdown behaviour of two low pour point synthetic ester liquids is presented in comparison to a typical synthetic ester at both positive and negative polarities. Traditional mineral insulating oil has been also considered for reference purposes. A detailed breakdown behaviour analysis of the four test liquids under a non-uniform field (medium gap, point-plane electrode system) and quasi-uniform field (smaller gap, U-plane electrode system) is envisaged. The lightning impulse breakdown measurements based on the source voltage waveforms and light activity during the discharge process are presented. The Weibull breakdown failure rates and streamer velocity during the breakdown of different liquids for all the cases (+/- polarities and both electrode configurations) are reported in support of the discussions. In the case of non-uniform fields, the lightning breakdown voltage of the low pour point liquids is found to be higher than typical synthetic esters and is comparable to mineral oil under both polarities. While in the case of quasi-uniform field, the lightning breakdown voltage of the low pour point liquids is found to be lower than mineral oil and comparable to the typical synthetic ester under both polarities. These findings add to limited knowledge on the application of esters in cold countries and allow insulation designers to estimate the behaviour of the low pour point synthetic ester liquids under lightning conditions.

4.1. INTRODUCTION

Power transformers are one of the expensive components connected to the electric power network. Any unscheduled outages of a transformer will directly influence the reliability of the power supply to customers. It is reported that the insulation system contributes largely to a majority of transformer outages [1, 2]. Therefore, studies concerning transformer insulation systems, are essential from technical and economic perspectives. Ester-based insulating liquids have gained tremendous interest as a potential alternative to traditional mineral oils. Numerous reports in the literature are affirmative towards the application of these new liquids in transformers for a safe and improved performance [3, 4]. However, the application of ester based dielectric liquids for transformers in cold countries is still a challenge to electric power utilities and transformer owners. The wide acceptance of these environmentally friendly dielectric liquids is questionable due to various technical reasons. The discussions concerning challenges of using esters in cold regions have been discussed by the author's group in [3, 5, 6]. Lately, low pour point synthetic ester based dielectric liquids have been developed by the industry for applications in cold climatic regions. However, a detailed understanding of these liquids is essential for dielectric engineers for an effective design and safe operation.

Prebreakdown phenomena and breakdown behaviour of insulating liquids are important electrical aspects that play a major role in the dielectric design of an insulation system. These aspects are majorly dependent on the electrode configuration, type/state of the liquid, and nature of the voltage [7, 8, 9]. It is to be recalled that this behaviour is analyzed based on the characteristic nature of the streamers during their initiation and propagation [10, 11]. It is customary to study the behaviour of streamers by physical, electrical, and optical parameters [7, 12, 13]. The physical parameters include streamer shape, stopping length, and propagation velocity, while the electrical parameters include initiation voltage, acceleration voltage, breakdown voltage, and leakage current. The optical parameters deal with the properties of light realised during the streamer propagation, generally recorded using a photomultiplier tube or analyzed using spectral approaches. There is abundant literature, reviewed in [7, 14], on the understanding of the dielectric behaviour of the ester based dielectric liquids (both natural and synthetic). The literature and existing standards are focused on comparing the behaviour of streamers in esters to that of streamers in mineral oils. This direct comparison allowed to have a common reference and simple understanding of the prebreakdown and breakdown phenomena in typical ester liquids.

However, very limited literature is available on the behaviour of streamers in low pour point insulating liquids. The influence of the needle tip radius (HV electrode) and aging decay particles on streamer behaviour in low pour point synthetic ester liquids via-a-vis mineral oils under AC stress is reported in [5]. It is noticed that the chemical changes incurred due to degradation, acidity, and concentration of decay products directly impact the streamer behaviour and this phenomenon in low pour point synthetic ester liquids is comparable to mineral oils. Recently, the prebreakdown phenomena of low pourpoint synthetic ester liquids (aged and non-aged) via-a-vis mineral oils and typical synthetic esters have been analysed under negative lightning impulses for the case of a point-plane electrode with medium gap [15]. From the study, it is observed that the streamer inception and breakdown voltages of low pour point esters are similar to mineral oil. However, the influence of the impulse polarity, behaviour at minus and hotspot temperatures, and short gaps with quasi-uniform fields is yet to be explored in the case of low pour point synthetic ester liquids.

As per CIGRE 549 [16, 17], a majority (approx. 90%) of the impulse strokes, experienced in the northern hemisphere of the globe, is negative type. However, it is also reported that the cold climatic conditions favor the occurrence of positive polarity impulses. It is known that the positive polarity impulses are rigorous in nature and leave a detrimental impact on the insulation system compared to that of the negative type [7, 14]. Henceforth, there is high importance for studies dealing with positive polarity, especially for insulation systems designed for cold climatic conditions. Thus, in this work, the influence of polarity on the breakdown behaviour of the low pour point synthetic ester liquids under non-uniform and quasi-uniform fields is investigated.

The present work reports the lightning impulse breakdown analysis of mineral oil (MO), two low pour point synthetic esters (SE1 and SE2), and a typical synthetic ester (TSE). The analysis is carried out under two different electrode configurations to show possible influence of field nonuniformity on results obtained. The lightning impulse breakdown measurements supported by the light activity during the streamer propagation are reported. The Weibull breakdown failure rates and streamer velocities are computed for all the test liquids under positive and negative type impulses. This allowed to analyse the impact of impulse polarity on the breakdown behaviour of the test liquids. This study adds to the existing literature on the breakdown behaviour of the low pour point synthetic ester liquids. The discussions in this article are helpful in scaling the performance of the low pour point synthetic ester liquids in reference to the typical synthetic esters.

4.2. LIGHTNING IMPULSE POLARITY: BACKGROUND

Lightning is a natural and atmospheric phenomenon involving a high and rapid exchange of charges between two electrically charged bodies. Depending on the direction of the flow of electrons, lightning is categorized into positive and negative polarity. This lightning is also seen between cloud to ground or cloud to other bodies on the earth. It is known that 90% of these activities contribute to negative lightning while the other 10% is accountable for the positive lightning flashes [16]. While both negative and positive lightning is accomplished in a very short transit of time, the positive ones are more rapid and typically are stronger strokes. It is to be recalled that the positive streamers travel in a single stroke while the negative streamers travel in more than two strokes. This can also be validated by the filamentary shape and the bushy (with side branches) shape of positive and negative streamers in insulating liquids under standard lightning impulse stresses, respectively. The occurrence of these lightning strokes is dependent on many atmospheric and geographical (location) aspects. However, Nordic regions, winter thunderstorms, and thunderclouds formed by the smoke (due to forest fires) favor the occurrence of positive lightning impulses [16].

The lightning strokes may generally cause damage to electrical equipment like power transformers that are exposed to atmospheric conditions. Therefore, the research in the field of high-voltage engineering also aids in various monitoring and design aspects of insulation for safeguarding electric equipment. Typically, the research is largely emphasized on the negative polarity impulses because of the fact that the streamers are slower, and the characteristics could be well understood. However, it is to be noticed that the highly energetic positive streamers are likely to cause more damage/destruction than negative ones [18]. Hence the dielectric design aspects of any insulation system must consider the behaviour under positive impulses due to the high risk involved. Specially for the insulation systems that are foreseen being installed in the northern hemisphere, cold regions, and high forest fire areas.

To date, the research on the prebreakdown and breakdown of insulating liquids under lightning impulses is generally focused on the negative polarity, summarised in [7, 14]. However, the influence of polarity on the streamer propagation velocities is also a subject of research for a few studies [19, 20]. Due to various reasons reported in the previous section and author’s recent articles [5, 6, 15], the low pour point ester liquids have been the target test liquids. It is to be understood that these prebreakdown phenomena and breakdown behaviour under impulse conditions are not yet explored. Since these liquids are expected to be operated successfully in the transformers serving cold regions, the influence of polarity on the breakdown behaviour is a topic of interest and would add to the existing knowledge.

4.3. EXPERIMENTAL

4.3.1. TEST LIQUIDS

As discussed, the present work reports the prebreakdown behaviour of low pour point dielectric liquids. Hence, the liquids having a pour point less than -50 ºC are studied [5]. The traditional mineral oil and typical synthetic ester also met this low pour point condition. The non-aged liquids are subjected to degassing for 48 hours under vacuum at room temperature, followed by dehydration for 48 hours at 60 ºC for mineral oils and 70 ºC for ester liquids. This pretreatment allowed the removal of any stray gases or moisture present in the test liquids. The basic properties of the test liquids are presented in Table IV. 1.

TABLE IV. 1.Properties of the test liquids

Property	Units	Test liquids			
		MO	SE1	SE2	TSE
Pour point	ºC	-51	-75	-65	-56
Fire point	ºC	148	220	284	316
IFT	mN/m	40	26	25	26
TAN	mgKOH/g	0.01	0.01	0.01	0.01
Density@20ºC	Kg/m3	0.88	0.91	0.95	0.97
Viscosity@20ºC	cSt	7.5	50	30	110

AC BDV	kV	63	60	65	62
Moisture	(ppm)	10	20	40	50

4.3.2. MEASURING SETUP AND ELECTRODE CONFIGURATIONS

The test liquid is placed in the test cell where the electrode arrangement is employed. The high-voltage electrode is used to subject to the voltage from the source while the opposite electrode is grounded. The present study uses a six-stage Marx generator (500 kV) with a stored energy of 2.2 kJ to generate test voltage. The lightning impulse generator (LIG) supplies the standard lightning impulse voltage (1.2/50 μs) to the high-voltage electrode. The applied voltage is measured using the peak value meter (PVM) and a voltage divider (resistive) with a voltage ratio equal to 1000. A digital oscilloscope (OSC) is deployed to record the light activity and the source voltage waveforms. An optical cable with a photomultiplier tube (PMT) having an operating range from ultraviolet to infrared (300 to 850 nm) is utilized to detect the inception and propagation of the streamers. This is because the most intense discharges are witnessed by the emission of light in the range of 300 nm to 360 nm [12, 21]. The schematic of the measuring setup is shown in Figure IV. 1.

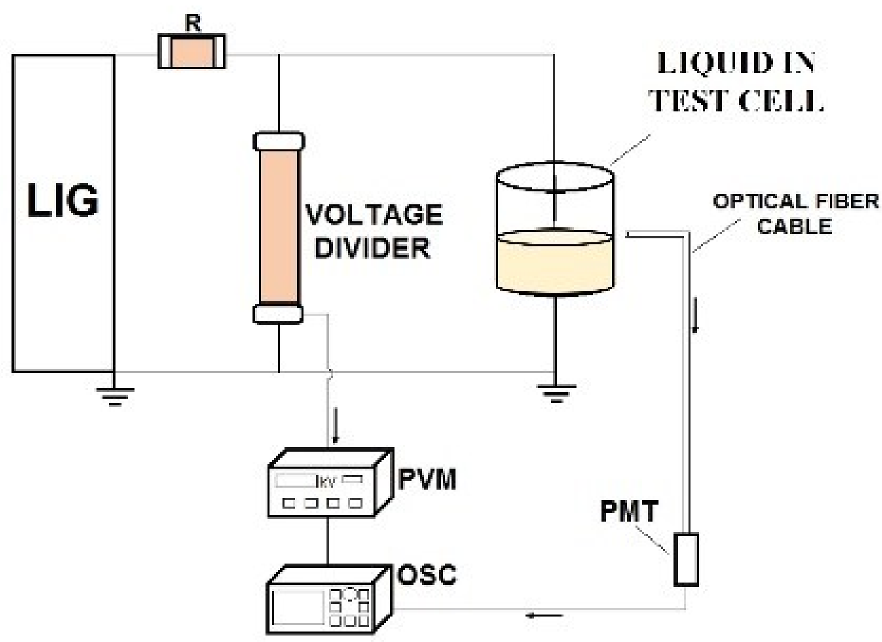


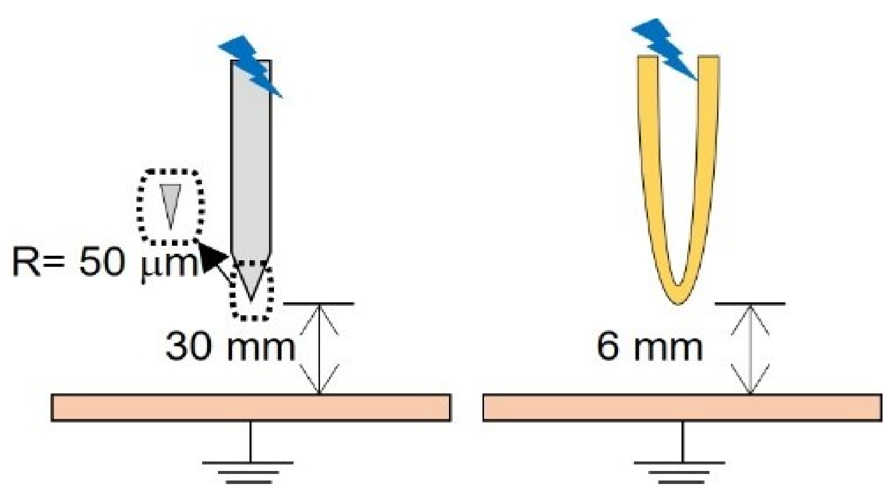
Figure IV. 1. Schematic of the measurement setup.

As discussed, two different electrode configurations, namely point plane and U-plane, are utilized to test all four insulating liquids in the present study.

Point plane: The point-plane electrode is utilized to represent the non-uniform fields. The point electrode (high-voltage electrode) is a tungsten needle with 50 μm of tip radius. The plane electrode (ground electrode) is a copper plate with a diameter of 3.5 cm. The inter-electrode gap (the distance between the needle tip and plane) is maintained at 30 mm. The point-plane electrode scenario does not practically occur in the transformers. However, this configuration has been widely accepted for decades for the laboratory-based experimental analysis of transformer insulating liquids and is more suitable for studies based on streamer analysis [7].

U-plane: The U-plane electrode is used to represent the quasi-uniform fields. It may represent the electrical stresses occurring on the cable corner in the oil duct located between the windings in the radial insulation system of the transformer. The "U" electrode (high-voltage electrode) is a round brass wire that is bent to a "U" shape. The tip of the bent is milled on both sides, thus leaving a point shape to the side view of the "U." Milling is carried out to intensify the electric field and ease the discharge process from this area. The plane electrode (ground electrode) is a copper plate with a diameter of 15 cm. The inter-electrode gap, in this case, is maintained at 6 mm.

The details and view of the electrode configurations used for present testing are presented in Figure IV. 2.



(b)

Figure IV. 2. The electrode configurations used for testing: a) Point-plane, b) U-Plane.

4.3.3. TESTING PROCEDURE

As per the IEC 60897 testing procedure, the subsequent lightning impulse steps supplied to the electrode system are assumed to be U=5 kV. A time lag (t) of one minute is maintained between each step, as per the IEC 60897. This rise in voltage steps with a one-minute delay is continued until the lightning impulse breakdown (LIBV) is realized between the electrodes. This is now referred to as one LIBV series, and a total of 10 series measurements are performed with a time lag (T) of 5 minutes between each series. The average of the 10 LIBVs is considered as the LIBV of a test liquid at the said condition. It is to be mentioned that after every 10 measurements, the needle electrode and the “U” electrode are replaced. This allowed us to maintain a consistent high-voltage electrode tip while countering the blunting witnessed due to shock waves generated during the impulse discharges. Due to the difference in the breakdown voltages for different polarities [7, 8, 20, 18] and based on the experience, different levels of initial values are employed by the authors for different polarities.

For Positive Polarity: The lightning impulse breakdown voltages in positive polarity and non-uniform fields are generally lesser than in negative polarity. Therefore, the starting voltage of the impulse generator is set to 55 kV (initial value) with a positive polarity for the first step.

For Negative Polarity: The lightning impulse breakdown voltages in negative polarity generally are on a higher level. Thus, the starting voltage of the impulse generator has been set to 75 kV (initial value) with a negative polarity for the first step. The schematic of the testing procedure is indicated in Figure 3.

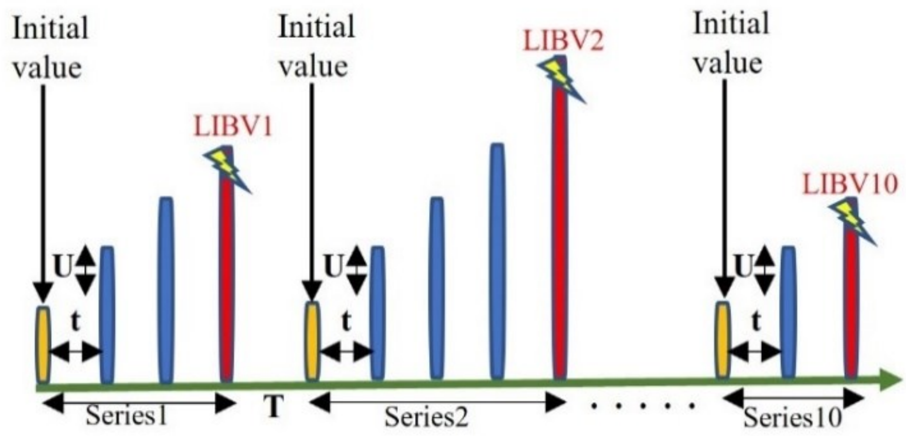


Figure IV. 3. Procedure of the LIBV measurement: LIBV1, LIBV2, LIBV10 – subsequent LIBVs (1, 2, .. 10), U –voltage step, t – time lag between two subsequent voltage steps (1 minute), T – time delay between subsequent measurement series (5 minutes).

4.4. MEASUREMENTS AND OBSERVATIONS

This section presents the details of measurements and observations on the results obtained in the case of both the electrode configurations for positive and negative polarities. In addition, the time to breakdown (TTB) is also presented in all the cases. Time to breakdown is the time taken by a liquid from the beginning of the voltage to until a sudden collapse of the voltage is noticed. It is to be understood that this collapse in voltage is due to the realization of the breakdown. The TTB is achieved by reading the OSC registrations of the light and voltage waveforms for each case.

4.4.1. NEGATIVE POLARITY

4.4.1.1. POINT PLANE ELECTRODE

The results of the lightning impulse breakdown under negative polarity for the point plane electrode system are presented in Table IV 2. The LIBV values presented here are the average of the values concerning 10 series measurements. Similarly, the values of the average time to breakdown and corresponding standard deviations are also presented in Table II. The oscillograms registered for the source voltage and light activity during the breakdown process under the negative point plane electrode configuration for four test liquids are illustrated in Figure IV. 4.

TABLE IV. 2. LIBV for Point-Plane Electrode Under Negative Polarity

Test Liquid	LIBV (kV)		TTB (µs)	
	Avg.	Std. Dev.	Avg.	Std. Dev.
MO	122	5.37	33.5	1.64
SE1	120	4.08	25.66	3.78
SE2	117	4.83	28.75	4.26
TSE	105.5	2.83	32.8	2.16

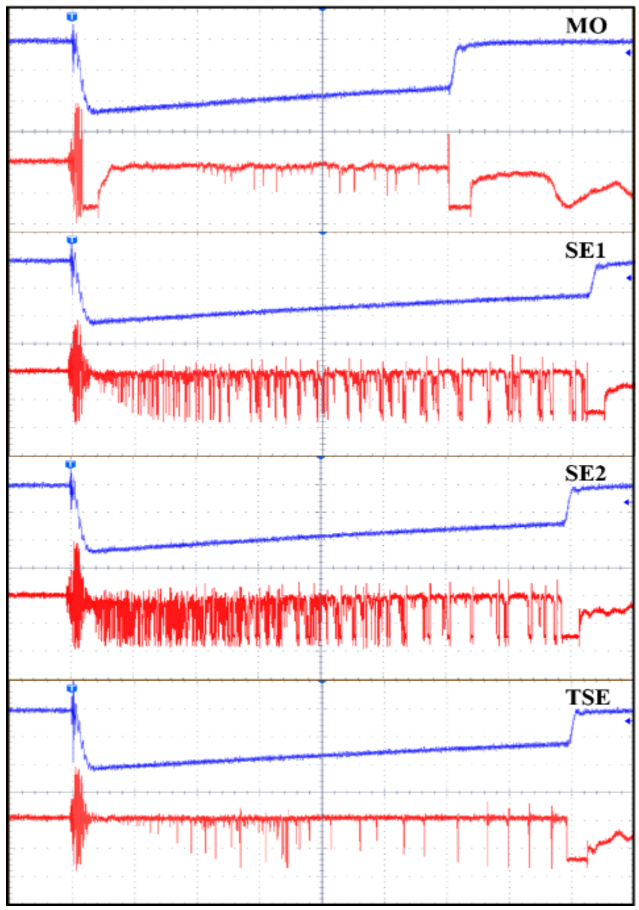


Figure IV. 4. Oscillograms of LIBV and light activity during the discharge process in various test liquids with point plane electrode configuration under negative polarity, t = 4 µs/div. V = 50 kV/div.

It is observed that the low pour point synthetic ester liquids (SE1 and SE2) have a 10 to 12% higher LIBV than that of the typical synthetic ester and have comparable values to that of the mineral oil. While the typical synthetic ester has a lesser LIBV than that of the MO (almost 14% higher than TSE), which is in line with the previous literature [7, 14, 20]. In the case of time to breakdown values, it is observed that the SE1 and SE2 have only slightly less time to breakdown than in case of mineral oil. This means that the low pour point liquids possess very similar dielectric withstanding ability for this condition. Also, the standard deviation values of the LIBV indicate a higher data dispersion in the case of the mineral oil as compared to the other three test liquids. This indicates the stability of the electric field in the case of synthetic ester liquids (SE1, SE2, and TSE) under non-uniform electric field conditions. This observation is in line with the existing literature on mineral oil and typical synthetic ester liquids [7, 14, 20]. The registry of the light activity indicates a higher light intensity, and probably more dense streamers (could be main or branching) are witnessed in the case of the low pour point liquids. It is to be recalled that the electric field in the case of the point plane is non-uniform, and the streamers in negative polarity are not rigorous. Thus, allowing a possibility and scope for side-branching streamers.

4.4.1.2. U-PLANE ELECTRODE

The results of the LIBV (average of 10 measurements) for the U-plane electrode system under negative polarity are presented in Table IV. 3. Also, the values of the average time to breakdown and corresponding standard deviations are tabulated in Table III. The oscillograms registered for the source voltage and light activity during the breakdown process under negative polarity and U-plane electrode system for four test liquids are illustrated in Figure IV. 5.

TABLE IV. 3. LIBV for U-Plane Under Negative Polarity

Test Liquid	LIBV (kV)		TTB (µs)	
	Avg.	Std. Dev.	Avg.	Std. Dev.
MO	87	4.21	5.2	1.03
SE1	80	2.35	4.37	0.91
SE2	79	2.10	5	0.66
TSE	79	3.16	4.5	0.52

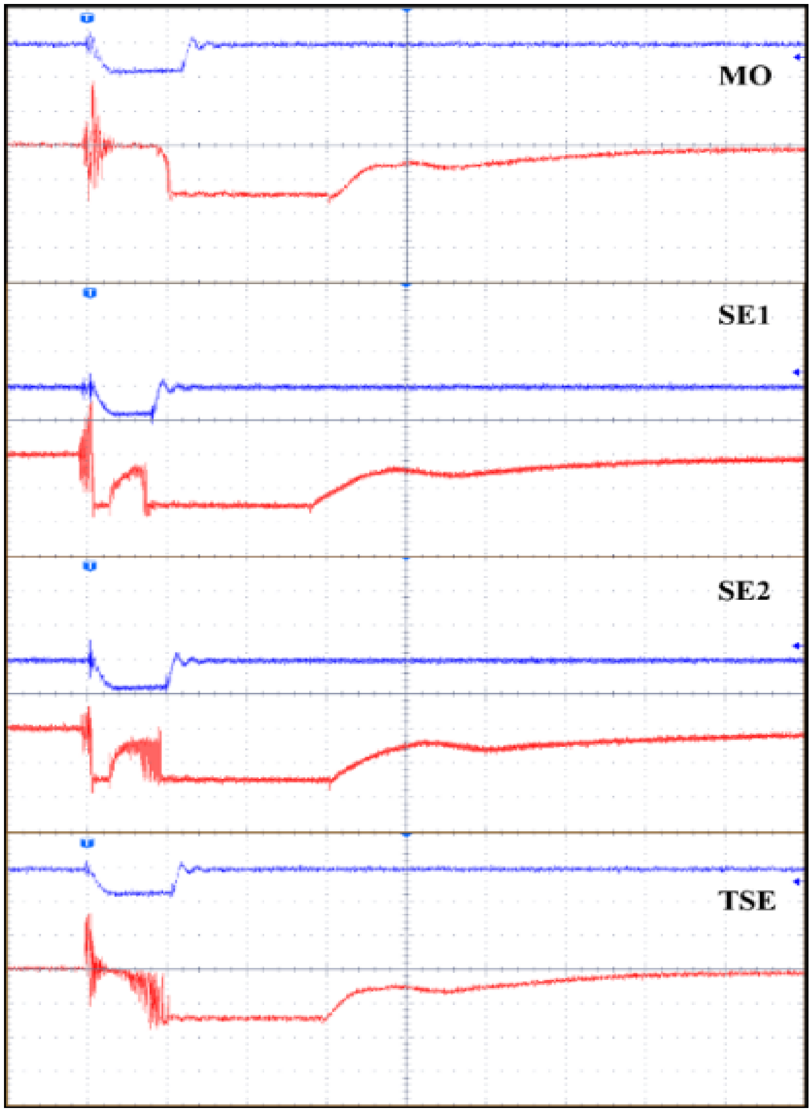


Figure IV. 5. Oscillograms of LIBV and light activity during the discharge process in various test liquids with U-plane electrode configuration under negative polarity, t = 4 μs/div., V = 100 kV/div.

The LIBVs of the low pour point synthetic ester liquids (SE1 and SE2) are found to be comparable to that of the LIBV of the typical synthetic ester under a negative U-plane electrode. However, the LIBV of the MO is found to be circa 10% higher than that of the other three test liquids. Also, the standard deviation values of the LIBV indicate a higher data dispersion in the case of the mineral oil as compared to the other three test liquids. It seems more stable behavior of synthetic ester liquids (SE1, SE2, and TSE) even in quasi-uniform electric fields. On the other side, the time to breakdown is highly comparable in all four. This is possibly due to the smaller inter-electrode gap (6 mm) of the U-plane configuration. The light activity, for all cases, is hot high in the period of time preceding breakdown. This is due to a more uniform field (compared to the point-plane electrode system) and the mentioned small gap. In turn, a high intensity of light sustained for a while after the complete voltage collapse (LIBV) is evident, what is confirmed through the constant PMT waveform component following the breakdown.

4.4.2. POSITIVE POLARITY

4.4.2.1. POINT PLANE ELECTRODE

The results of the average lightning impulse breakdown and average time to breakdown under positive polarity for the point plane electrode system are presented in Table IV.4 . The oscillograms registered for the source voltage and light activity during the breakdown process under the positive point plane electrode for four test liquids are illustrated in Figure IV. 6.

TABLE IV. 4. LIBV for Point-Plane Electrode Under Positive Polarity

Test Liquid	LIBV (kV)		TTB (µs)	
	Avg.	Std. Dev.	Avg.	Std. Dev.
MO	76	5.16	15.5	2.34
SE1	78.5	2.41	10.33	1.5
SE2	79	5.16	8.37	3.15
TSE	75	4.08	14.62	0.5

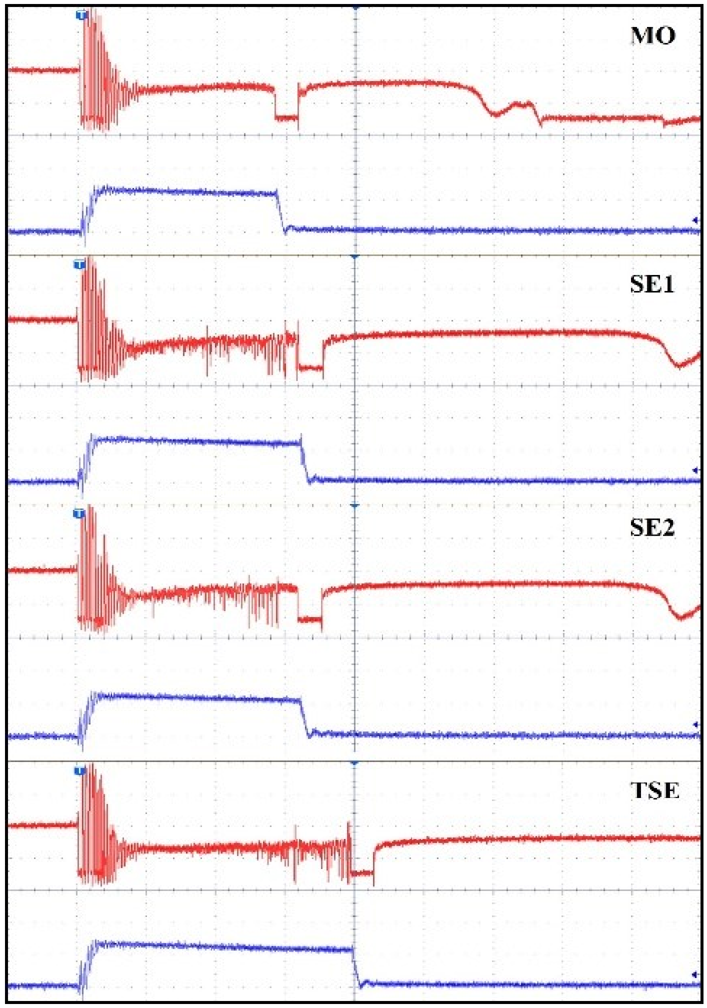


Figure IV. 6. Oscillograms of LIBV and light activity during the discharge process in various test liquids with point plane electrode configuration under positive polarity, t = 4 μs/div., V = 50 kV/div.

The LIBV of the low pour point synthetic ester liquids is found to be 3 to 4 % higher than that of mineral oil and typical synthetic esters. On the other side, the time to breakdown in the case of SE1 and SE2 is, as in the case of negative polarity, less than that of mineral oil and typical synthetic ester, this time with the factor of circa 40%. It is seen from the oscillograph that the light activity is considerably low under positive polarity in the case of non-uniform fields.

4.4.2.2. U-PLANE ELECTRODE

The results of the average lightning impulse breakdown under positive polarity for the U-plane electrode system are presented in Table IV. 5 together with corresponding values of the average time to breakdown and the standard deviations for both quantities. The oscillograms registered for the source voltage and light activity during the breakdown process under the negative U-plane electrode for four test liquids are illustrated in Figure IV. 7.

TABLE IV. 5. LIBV for U-Plane Electrode Under Positive Polarity

Test Liquid	LIBV (kV)		TTB (μs)	
	Avg.	Std. Dev.	Avg.	Std. Dev.
MO	86	5.16	3.1	0.56
SE1	72.5	2.63	2.22	0.44
SE2	76	3.94	2.33	0.70
TSE	76.5	6.68	2.8	1.03

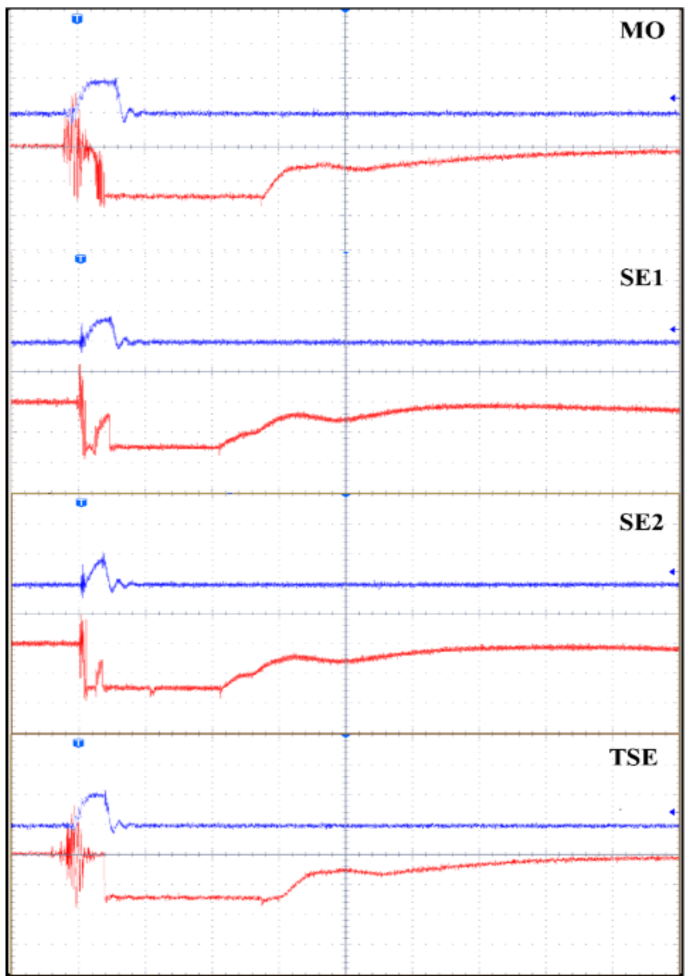


Figure IV. 7. Oscillograms of LIBV and light activity during the discharge process in various test liquids with U-plane electrode configuration under positive polarity, t = 4 μs/div., V = 100 kV/div.

The LIBV of the low pour point synthetic ester liquids is noticed to be comparable to that of the typical synthetic ester and lower when compared with MO. It is worth noting that the values obtained are only slightly lower than the results concerning negative polarity. It is an effect of field uniformity (and small gap in lesser extent) more uniform field reduces differences in LIBV between the polarities. In terms of the standard deviation values the LIBV for SE1 and SE2 are, as in the case of negative polarity, lower than that of the mineral oil and TSE. This indicates a stable situation in case of both low pour point synthetic esters and less field nonuniformity. The time to breakdown is less in the case of SE1 and SE2 than in the case MO and TSE; this may be attributed to the smaller electrode gap and the polarity (positive). It is also to be noted that the constant PMT waveform component following the breakdown is noticed in all the cases. This indicates an intense process following the breakdown phenomena

4.5. DISCUSSIONS

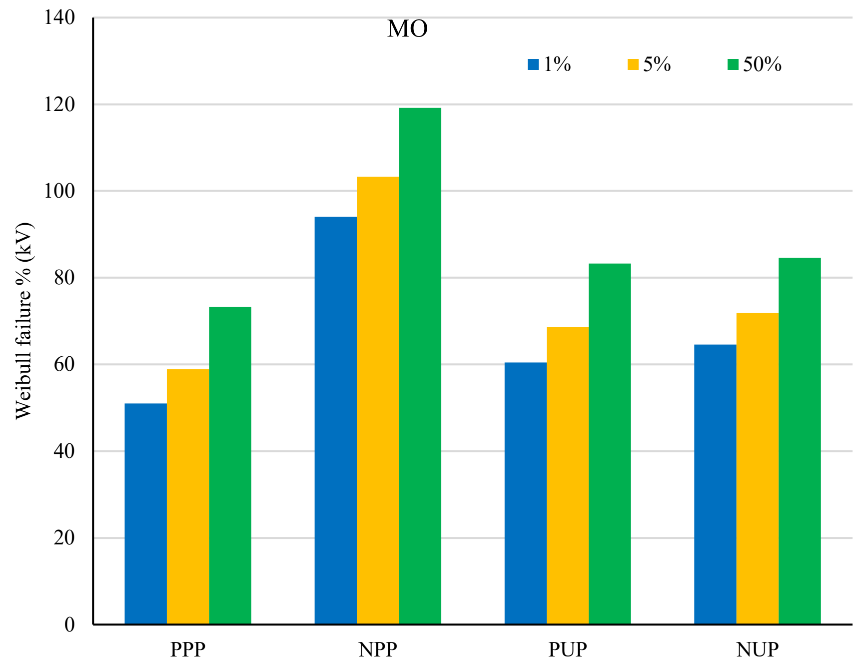
It is obvious from the results that the LIBV behaviour of the liquids changes with the impulse polarity and other experimental conditions considered herein. This section presents a detailed discussion of the results to better understand the LIBV behaviour of the test liquids. This section aims to analyze the results obtained while understanding the influence of the type of liquid, electrode configuration, and polarity on the LIBV behaviour of the low pour point insulating liquids.

In general, it is widely reported that due to differences in the molecular structure, the type of liquid influences the breakdown properties of a liquid [7, 14, 18]. Several works have attempted to improve the dielectric properties of the liquid by means of chemical modification [18, 22]. In some situations, the aim to improve the ester liquid properties, such as oxidation stability, viscosity, pour point, and ionization resistance attained by means of various additives, is witnessed in the literature [23]. In the present study, two low pour point synthetic esters and a typical synthetic ester liquid are investigated. It is to be understood that these low pour point liquids are fundamentally ester group liquids, of course, with certain additives to reduce pour point for applications in cold regions.

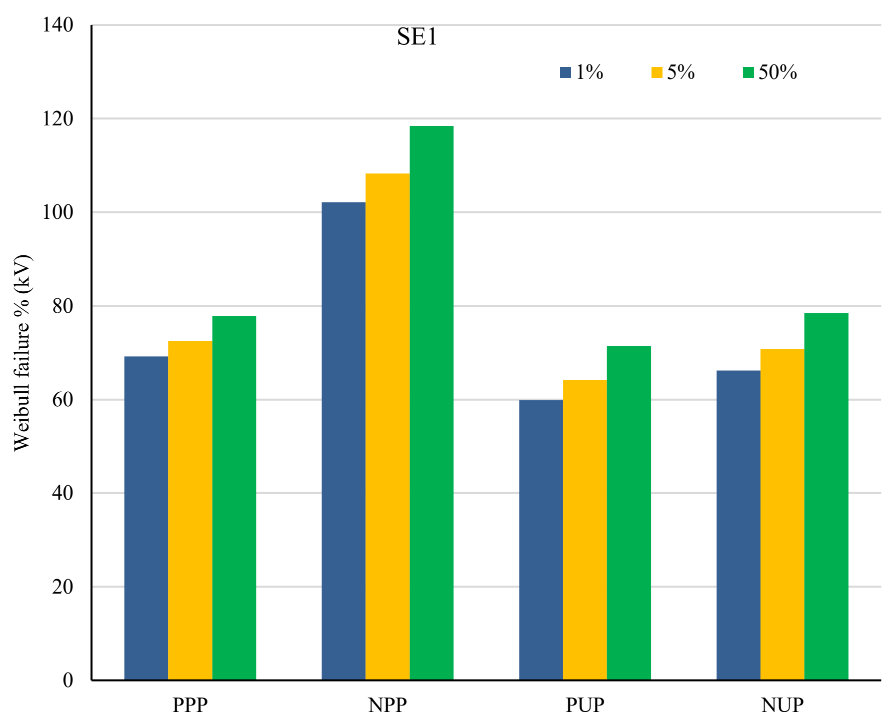
Fundamentally, ester liquids are polar in nature, while mineral oils are non-polar liquids. This molecular difference has made a great difference in terms of degradation (especially with oxidation products) and the water holding ability of esters. Also, polar molecules have a lower ionization potential, the ions are liberated more easily than that of hydrocarbon mineral oils. This is counterpoised by adding electronic scavengers to the liquid [22]. Due to less oxidation stability and glycerin concentration, application of esters in cold climatic regions is questionable [24]. The popular approach to improve oxidation stability and reduce the pour point is to add inhibitors and pour point depressants, respectively, into the liquid. Concerning the pour point in the case of esters, the other possible approach is to reduce the glycerin content in the liquid to modify its viscosity profile. This will leave the liquid to exhibit lesser viscous forces on a molecular level, even at low temperatures. The water saturation limit of esters reduces at low temperatures and hence impacts the dielectric performance as well. All the above molecular properties and chemical modifications may lay an impact on the liquid breakdown properties.

Weibull failure probability analysis is widely accepted to understand the serviceability and reliability of the insulation liquids [7, 14, 18, 25]. Since the 50% probability is not generally of interest in engineering practice lesser failure probability percentage values are used in most cases for comparative analysis of the data. Hence, the 1%, 5%, and 50% Weibull failure percentages calculated from the LIBVs of the test liquids for non-uniform fields and quasi-uniform fields at both voltage polarities are presented in Figure IV. 8.

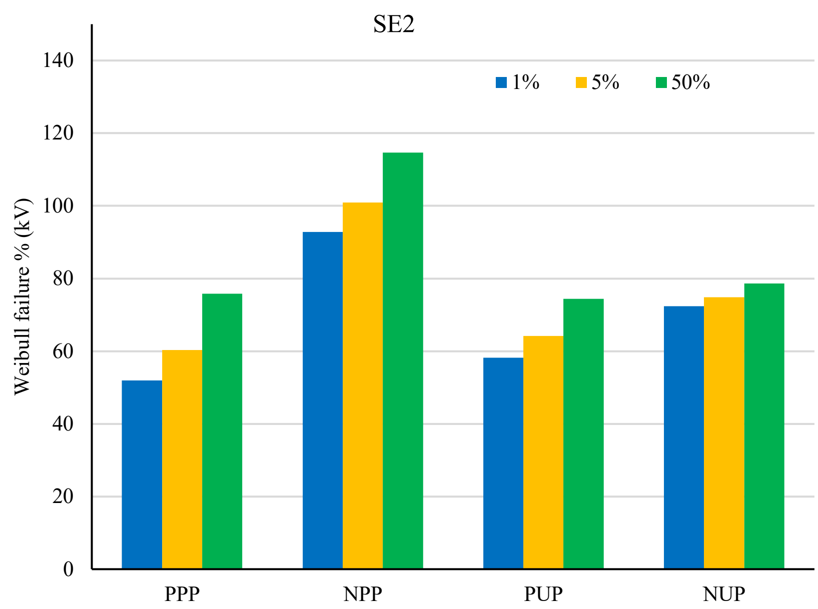
Here PPP and PUP are point plane and U-plane electrode configuration under positive polarity while NPP and NUP are point plane and U-plane electrode configuration under negative polarity. As was expected, for a point plane electrode system representing non-uniform field distribution, it is clearly seen from the graphs presented that the influence of the voltage polarity is unequivocal. The LIBVs are higher for negative polarity, and the relationship noticed between the polarities is similar no matter which liquid is considered. However, a small deviation is noticed for TSE, where the difference between positive and negative LIBV is the smallest.


MO
1%
5%
50%
Weibull failure % (kV)
140
120
100
80
60
40
20
0
PPP
NPP
PUP
NUP

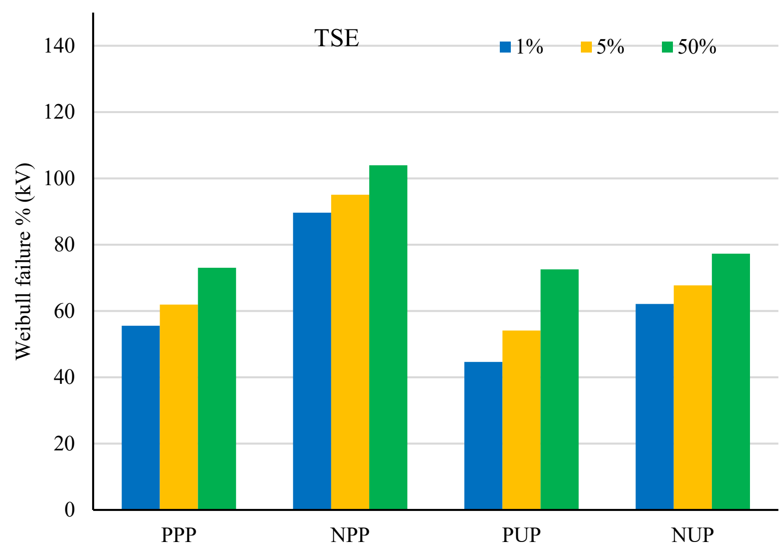
(a)


SE1
1%
5%
50%
Weibull failure % (kV)
140
120
100
80
60
40
20
0
PPP
NPP
PUP
NUP

(b)



(c)



(d)

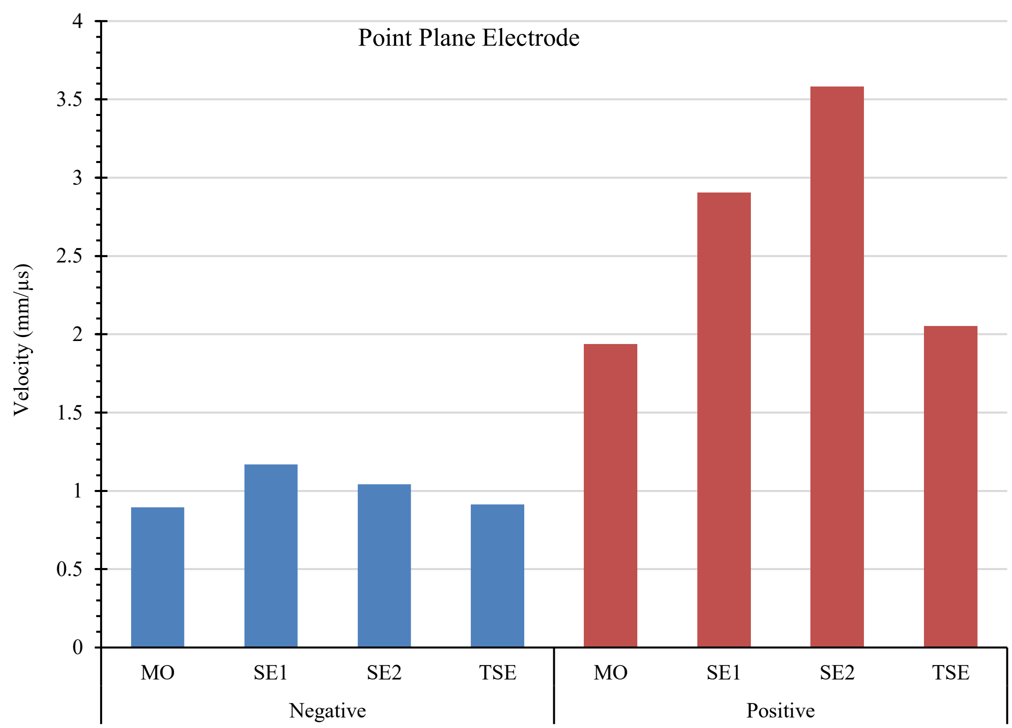
Figure IV. 8. Weibull failure probability percentages of the LIBV of the test liquids, (a). MO, (b). SE1, (c). SE2, (d). TSE.

Independently of which breakdown probability is considered, the above observation is valid without exception. When comparing the data concerning U-plane electrode configuration, which represents less nonuniformity of field distribution than in the case of point plane electrode system, the negative and positive LIBVs are closer to each other. The differences between polarities are on the level of the individual percentage, and again this statement concerns equally all liquids tested. An exception is observed for TSE, which is the liquid most different from the others. On the basis of this type of consideration, this may be said that, based on the conditions of the experiment, modifications causing the lowering of the pour point of synthetic esters have not worsened their dielectric properties in terms of lightning impulse stress. The chemical structure of low pour point synthetic esters made them more resistant to lightning impulse voltage than a traditional synthetic ester, with simultaneous closing up to the tested mineral oil.

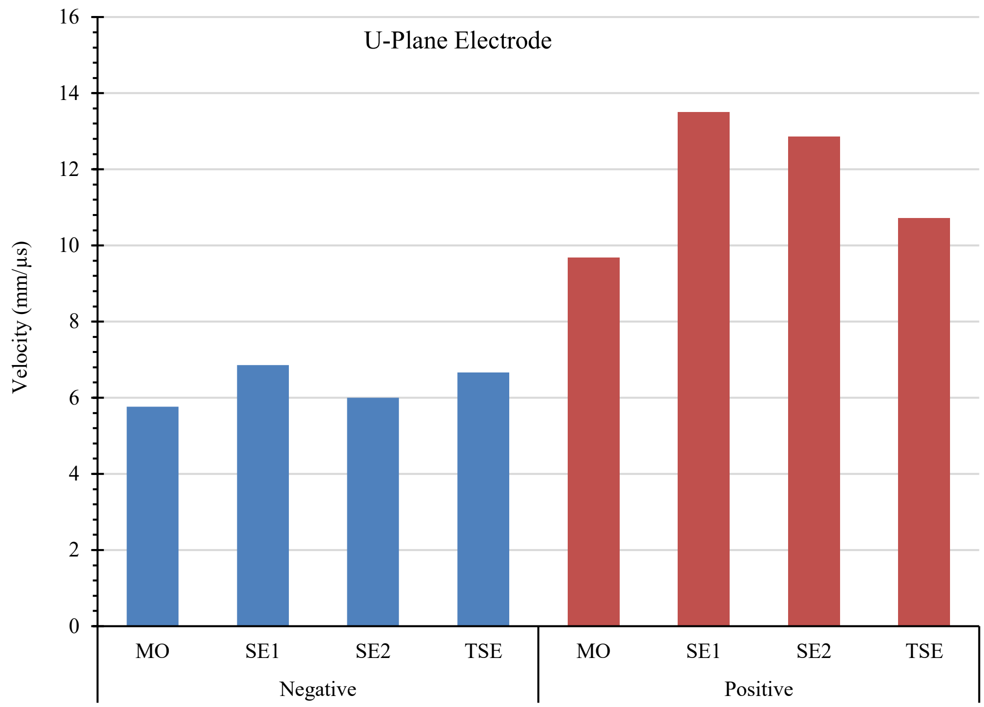
When discussing the influence of the electrode configuration on the lightning behavior of tested liquids, it was noticed that this influence is marginal. It means that the change of field uniformity has not influenced the general differences between liquids. Independently of the electrode configurations, low Weibull failure probabilities are very close to each other in the case of MO and both low pour point synthetic esters SE1 and SE2. Also, the traditional synthetic ester TSE, which was characterized by lower LIBV when comparing average values, does not differ significantly from other liquids when setting together 1% breakdown probabilities. In general, the data fluctuates, indicating that sometimes one liquid is better and sometimes another, which is in accordance with some reports presented in the literature [7, 8, 14, 18, 20].

Certainly, the greater dielectric stability of the SE1 and SE2 liquids at lightning impulse stress must be underlined based on the standard deviation data as well as the low dispersion of the values corresponding with different levels of breakdown probabilities read from Weibull distribution plots. It is a beneficial aspect in predicting their real applications, looking at behavior under lightning stress. Especially for the positive polarity of lightning impulse voltage, a lower difference between 1% and 50% breakdown probabilities characterize low pour point synthetic esters, particularly SE1. It is important to point out that this conclusion is valid for both electrode systems considered, so it may be said that electrode configuration (field nonuniformity) has a minor influence on the behavior of low pour point synthetic esters in relation to TSE and MO.

An important parameter of comparative nature is streamer propagation velocity. It is generally influenced by lightning impulse polarity, which also affects streamer energy when propagating. Propagation velocity is also controlled by the electric field, meaning the impact of the electrode configuration [4, 7, 11, 18]. For comparative purposes, the average streamer propagation velocities corresponding with LIBV conditions for all liquids tested and under both field non-uniformity are summarized in Figure 9. It is established that streamer in synthetic esters propagates faster than that in mineral oils, regardless of the impulse polarity and field nonuniformity. However, literature reports [7, 14, 20] that for small gaps of point plane configuration, this difference, especially for negative polarity, is little, and this is solely noticed by looking at the results from Figure IV. 9. For positive polarity and the same electrode system, faster streamers characterize low pour point esters, but it does not influence LIBV values as reported earlier.



(a)



(b)

Figure IV. 9. Average breakdown streamer propagation velocity, (a). Point plane electrode, (b). U-plane electrode.

In accordance with the data on point-plane configurations are the data obtained for the U-plane system. The relationships between liquids are almost identical but generally with higher propagation velocities, both for the negative and positive voltage polarity. These higher values are attributed to the type of electric field distribution. A more uniform field generates faster streamers when a breakdown occurs. We can also digress that streamers in small (6 mm) U-plane gaps practically do not form, and the observed phenomenon is the direct forming of a breakdown channel without evident pre-breakdown processes. In such a situation, time to breakdown does not include streamer development; hence it is short, and propagation velocity calculated from time to breakdown is not significantly informative in such a case.

4.6. CONCLUSIONS

The following conclusions are drawn from the current studies:

Special modifications of synthetic esters, causing lowering their pour point in order to apply them in cold regions, have not worsened their dielectric properties in terms of lightning impulse stress.

The influence of electric field non-uniformity on the general behavior of tested dielectric liquids is assessed to be marginal; in the case of point-plane configuration, the LIBV of low pour point ester liquids is found to be higher than typical synthetic esters and comparable to mineral oil, this statement concerns both voltage polarities and especially low breakdown probabilities from Weibull failure plots; in the case of U-plane configuration, the LIBV of low pour point liquids is found to be lower than mineral oil for both voltage polarities, but the difference noticed for 1% breakdown probability is really low; at the same time, the typical synthetic ester is characterized by the lowest values of LIBV under both polarities.

The differences in propagation velocities calculated for the 30 mm point-plane electrode gap are of minor scale; the data obtained confirmed the well-known fact of slightly lower velocities of streamers developing in mineral oil.

The data on streamers propagation velocities obtained for the 6 mm U-plane gap are of discursive nature and need to be further studied.

Further studies are needed to better understand the prebreakdown behavior of low pour point synthetic esters, focusing on the intrinsic streamer properties. Also, comparing these results to the behavior of silicon liquids [26], of course, considering the opposite tendency for the pour points, may add merit to the overall findings. Evaluating the properties by considering the bio based mineral insulating oil may add merit.

CHAPTER V
CONCLUSIONS

5.1. CONCLUSIONS FROM THE RESEARCH

This research reports investigations on the performance of the pour point ester liquids for potential applications in transformers serving in cold regions. The present research is focused on the pre-breakdown and breakdown behavior under different experimental conditions. The current research is also focused on understanding the viability of the reclamation of ester liquids using adsorbents. The research carried out may be helpful for utility engineers and transformers owners. In addition, the proposed investigations will contribute to the existing knowledge of ester liquids.

The main conclusions from the research are listed below:

From the impulse testings, it is noticed that the inception and breakdown voltages of the non-aged low pour point synthetic esters are similar to non-aged mineral oil. In addition, the inception and breakdown voltages of the aged low pour point synthetic esters are noticed to be higher than that of the aged mineral oil. The thermal aging process has not influenced the acceleration voltage under the present experimental condition (non-uniform field and smaller gap distance).

In the case of non-uniform fields, the lightning breakdown voltage of the low pour point liquids is found to be higher than typical synthetic esters. It is comparable to mineral oil under both polarities. In the case of a quasi-uniform field, the lightning breakdown voltage of the low pour point liquids is found to be lower than mineral oil and comparable to the typical synthetic ester under both polarities.

In the case of regeneration, magnesium silicate-based adsorbents have some potential for the reclamation of synthetic esters (including low pour point liquids) by removing the polar compounds that occur with the service life of the liquid.

5.2. FUTURE RECOMMENDATIONS

For the continuity of this research topic and to address further aspects of the current topic, a few challenges that need attention are listed below:

Prebreakdown phenomena of low pour point ester liquids: Further studies, including to understand the intrinsic behaviour of streamers, are needed to better understand the prebreakdown behavior of low pour point synthetic esters. Also, experimental investigations (AC and Impulse) with insulated electrodes and understanding the impact of the barrier will add merit to the current findings.

Regeneration of synthetic esters: The study of other parameters to explore consists of the study of other adsorbents, adsorbent-liquid ratios, and the number of passes to be performed to achieve acceptable operational conditions for the reclamation of synthetic ester liquids. However, there is a need to investigate other reclamation procedures such as other methods of filtration, number of extractions or passes, cost of the adsorbents, ratio of adsorbent to oils, conditioning of the oils after reclamation to explore the feasibility of using these adsorbents. The retention analysis of the used adsorbents will also bring merit to better understand the efficiency and sensitivity of the reclamation. Also, the critical analysis of the treated liquid with further aging reveals the potential of the reclaimed liquid to serve as a dielectric liquid.

5.3. PUBLICATIONS FROM THE RESEARCH

- ***International Journals***

1. **T. Jayasree**, P. Rozga, I. Fofana, U. Mohan Rao, S. Brettschneider, P. Picher, M. Rodriguez Celis, "Prebreakdown and Breakdown Behaviour of Low Pour Point Dielectric Liquids Under Negative Lightning Impulse Voltage," **IEEE Transactions on Dielectrics and Electrical Insulation**, Vol. 30, No. 4, pp. 1470-1477, **2023.** doi: 10.1109/TDEI.2023.3274731.
2. **T. Jayasree**, I. Fofana, P. Rozga, U. Mohan Rao, K. Strzelecki, S. Brettschneider, P. Picher, M. Rodriguez Celis, "Analysis of Breakdown Voltage of Low Pour Point Synthetic Ester Insulating Liquids under Lightning Impulse Voltage of both Polarities," **IEEE Transactions on Dielectrics and Electrical Insulation**, vol. 31, no. 1, pp. 254-262, 2023. doi: 10.1109/TDEI.2023.3314706.

3. **T. Jayasree**, I. Fofana, E. M. Rodriguez Celis, P. Patrick, S. Brettschneider, “Reclamation of Synthetic Ester Dielectric Liquids by Pressure and Gravity Percolation Methods,” **IEEE Transactions on Dielectrics and Electrical Insulation** (*Under review*)

- ***Book Chapters***

4. P. Rozga, **T. Jayasree**, U. Mohan Rao, I. Fofana, P. Picher, “Prebreakdown and breakdown phenomena in ester dielectric liquids," Alternative Liquid Dielectrics for High Voltage Transformer Insulation Systems: Performance Analysis and Applications, Edition 1, pp: 147-183, **2021.**

- ***International Conferences***

5. **T. Jayasree**, P. Rozga, I. Fofana, U. Mohan Rao, S. Brettschneider, P. Patrick, E. M. Rodriguez Celis, “Streamer Inception and Breakdown Voltage of a Low Pour Point Synthetic Ester under Lightning Impulse, 22nd **IEEE DEIS International Conference on Dielectric Liquids,** Worcester, Massachusetts, U.S.A, June 2023 (***Best Student Paper Award***).
6. **T. Jayasree**, M. Rodriguez Celis, U. Mohan Rao, I. Fofana, P. Picher, S. Brettschneider, “Feasibility Study on the use of Magnesium Silicate for Reclaiming Synthetic Ester Insulating Liquid,” **2022 CIGRE Canada** Conference, Calgary, Oct. **2022.**
7. **T. Jayasree**, U. Mohan Rao, I. Fofana, S. Brettschneider, "Studying some Low Pourpoint Transformer Dielectric Liquids under Selected Conditions," 21st **IEEE DEIS International Conference on Dielectric Liquids**, Spain, **2022**.

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ANNEX I

ALTERNATIVE DIELECTRIC FLUIDS FOR TRANSFORMER INSULATION SYSTEM:

PROGRESS, CHALLENGES, AND FUTURE PROSPECTS

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ANNEX II

CONDITIONING OF TRANSFORMER INSULATION SYSTEM, PART 1: DEHYDRATION AND DEGASSING

The unpublished literature survey report, will be published in the future.

ANNEX III

CONDITIONING OF TRANSFORMER LIQUIDS, PART 2: REGENERATION AND RECLAMATION

The unpublished literature survey report, will be published in the future.

ANNEX IV

FEASIBILITY STUDY ON THE USE OF MAGNESIUM SILICATE FOR RECLAIMING SYNTHETIC ESTER INSULATING LIQUID

Article presented at the CIGRE Canada Conference, Calgary, Alberta, 31st October- 3rd November 2022

ANNEX V

INCEPTION AND BREAKDOWN VOLTAGES OF NEW LOW POUR POINT LIQUIDS UNDER LIGHTNING IMPULSE

Article presented at the IEEE 22nd International Conference on Dielectric Liquids (ICDL), Worcester, MA, USA, 2023