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Pre-Breakdown and Breakdown Behavior of Synthetic and Natural Ester Liquids under AC Stress

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Abstract: In the last decades, a large focus is being placed on the sustainability and safety of the power transformer spectrum. Ester liquids, which have interesting properties such as high fire point and biodegradability, are gaining needed attraction. Since in-service condition, thermal aging deteriorates the physicochemical and electrical properties of liquid dielectrics, it is important to study their long-term behavior. In this contribution, the pre-breakdown and breakdown behavior of ester fluids (synthetic and natural) under AC stress are investigated. Important characteristics, such as partial discharge pre-inception voltage, partial discharge inception voltage, breakdown voltage, average streamer velocity, and inception electric field, were assessed. The influence of the radius of curvature (of high voltage needle electrode) as well as the thermal degradation of typical ester liquids are also discussed. Mineral oil was also included in the tests loop as a benchmark for comparative purposes. It is found that the pre-inception voltage of ester liquids was, in most cases, higher than that of mineral oil. For a given radius of curvature, the streamer inception and breakdown voltages decreased with thermal aging. During the streamer initiation, the electric field at the electrode tip decreased with the increase in the radius of curvature. The velocity of the streamers seems to increase with the decrease in the radius of curvature. The period of vulnerability, the so-called "delay time", seems to be independent of the aging or the radius of curvature for a given condition of the liquid.

Keywords: breakdown voltage; partial discharge; power transformer; ester liquids

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1. Introduction

Mineral oil is commonly used, in liquid-filled transformers, as an insulating and cooling medium [1–3]. However, mineral oils are facing critiques in terms of environmental concerns [2]. In fact, the growing demand for petroleum products could lead to serious shortages even in the middle of the 21st century [4]. Natural ester and synthetic esters are considered as potential alternatives to mineral oil, due to their environmental advantages [5]. Indeed, the use of environmentally friendly dielectrics (biodegradable, non-toxic, edible, seed-based oil, etc.) is of increasing interest in the power industry. Natural and synthetic ester fluids are polar, as opposed to traditional mineral oils [6]. This reason allows the ester liquids to hold much higher water; this makes them hygroscopic. The difference between mineral oils and ester liquids is also reflected in their physicochemical properties. However, the environmentally friendly requirement is not enough to guarantee the use of ester fluid in power transformers. It is important to compare the physicochemical and electrical properties of both types of liquids (mineral oils and ester oils). Most of the literature on ester liquids is focused on the thermal degradation and service behavior, while a few are restricted to diagnostic studies and compatibility with other transformer materials, and the same are summarized in [2]. However, few researchers have also emphasized the pre-breakdown and breakdown phenomena of ester liquids, and the same is summarized in [2]. It is reported that the ionization resistance of ester liquids is inferior or comparable (in a few cases) to that of the traditional mineral oils. A few researchers have attempted to improve this characteristic using suitable additives (electron scavengers) and nanoparticles [2]. In the past few decades, the emphasis has been laid on the comparative study of some characteristics of streamers, in ester liquids and mineral oil, under lightning impulse voltage [7,8]. Few studies have dealt with the phenomenon of pre-breakdown and breakdown under AC stress with needle-plane configuration and different radius of curvature [9]. Comprehensive reviews of the present state of knowledge of pre-breakdown phenomena in liquid dielectrics are presented in [2,9,10]. Emphasis is laid on the fluid's chemistry, influence of pressure, and field distribution, etc. The review deals with different methods and procedures for the characteristics, such as partial discharge pre-inception voltage, partial discharge inception voltage, breakdown voltage, streamer velocity, and electric field. The details of various testing methodologies have been also included. The condition of the liquid has a noticeable influence on the breakdown behavior. This is because the degradation of transformer liquids is accompanied by the generation of decay products, water molecules, and other decay particles (generally conductive). These decay particles largely affect the ionization behavior of the liquid and are, in fact, detrimental to the insulation integrity of the transformer. The author's group has most recently reported the behavior of the same (aging particles) on the pre-breakdown behavior [11]. However, the same is restricted to low pourpoint synthetic ester liquids. Therefore, the current work is focused on typical, and commercially available, synthetic ester and natural ester insulating liquids.

This paper aims to study the pre-breakdown and breakdown behavior, under AC stress, in a point-plane electrode configuration at different tip radii and different aging conditions (liquid). The emphasis is laid on the electrical properties of mineral oil (MO), synthetic ester (SE), and natural ester (NE) liquids. Monitoring techniques, such as turbidity and UV-VIS spectroscopy, have been considered to correlate the liquids' degradation to the electrical measures. The study concerns the characteristics of streamers, including partial discharge pre-inception voltage, partial discharge inception voltage, breakdown voltage, streamer velocity, and electric field at the tip of the needle electrode. For this purpose, three needles of different tip radii are considered. In addition, the delay time (Δt), known as the period of vulnerability, has been computed. Based on the observations and inferences, critical conclusions have been drawn to report the influence of thermal aging on the pre-breakdown phenomena in typical ester liquids.

2. Background

The phenomena of electrical pre-breakdown and breakdown in liquid dielectrics are complex. Up to date, a generally accepted theory, explaining all experimental results, has not yet been established in the literature [10]. Some researchers suggest that the pre-breakdown and breakdown mechanisms are based on electronic processes such as collision ionization and intense electric field ionization [9,10]. Others advocate that it is due to a bubble (string of globules) formation mechanism. The digital technology and use of ultra-high-speed cameras and schlieren techniques have improved the understanding of these phenomena [2]. Some characteristics, such as shape, propagation velocity, and acceleration voltage, were studied by many researchers [2,9]. In particular, the study of streamer propagation velocity in liquid dielectrics has revealed four modes of propagation: 1st, 2nd, 3rd, and 4th mode of propagation. Typical streamer velocities are 0.1 km/s for the 1st mode, 2 km/s for the 2nd mode, 10 km/s for the 3rd mode, and 100 km/s for the 4th mode [12]. While a typical streamer is propagating in the bulk of the liquid, it is switched/transmitted from the 1st and 2nd modes (slow) to the 3rd and 4th modes (fast). The transition voltage between the slow and fast modes is observed by the tremendous increase in the streamer velocity. The study of the characteristics of streamers under lightning impulse voltage is widely discussed in the literature [13–16]. It is presented as a comparative study of the characteristics of streamers in MO, NE, and SE insulating liquids. The MO streamer characteristics are used as benchmark values for reference and comparative purposes with the ester liquids.

The physicochemical properties of the liquid dielectric influence the pre-breakdown and breakdown behavior when subjected to high electric field stress (as discussed in the previous section). In MO, only tens of parts per million (ppm) of absolute moisture content is sufficient to cause a rapid decrease in AC breakdown voltage, whereas for SE and NE, even up to a few hundreds of ppm of moisture content leave AC breakdown voltage at almost the same level [1]. Regarding the density and viscosity of SE and NE, experimental studies indicate that higher values of these two parameters may contribute to lower efficiency of transformer cooling capability [2,17]. It is also known that all these electrical and physicochemical properties changes are specific for each liquid and are dynamic in nature, with respect to the degree of deterioration [18,19]. A better understanding of the pre-breakdown and breakdown processes would allow for improving next generation transformer's design. This is because the performance of insulation geometries, inside transformers with esters, does not necessarily behave similarly to what it does in a mineral oil. Therefore, in this study, different liquids with a controlled aging history have been prepared for electrical and physicochemical testing, with the aim of understanding the influence of thermal degradation on the pre-breakdown properties. This is because, as discussed, the degradation is associated with the introduction of conducting particles to the liquid. These conducting particles (impurities) act as local weak points or stressed points for the ease of ionization. As long as these decay particles are available in the liquid, a number of processes, including avalanche formation and streamer propagation, are facilitated. Therefore, it is interesting to estimate the condition of the liquid in relationship with the pre-breakdown and breakdown behavior. The definitions, significance, importance, and literature concerning these individual factors are well explained in the author's previous work [16] and the review articles [2,9].

3. Experimental Setup and Preparation of Samples

3.1. Experimental Setup

The samples have been degassed and characterized based on fluid characteristics, including a turbidity test (HACH 2100AN Tubidimeter precision ±0.01 NTU) and a UV-VIS spectroscopy test (Thuramed Spectrophotometer T60 UV-VIS precision ±2 nm and ±1% for absorbance). For the electrical tests, three identical test cells and three tip electrodes, with different radii of curvatures, have been adopted. The details of the experimental setup (electrical measurements) of the present study is reported by the authors in the previous work [16]. For the present experiment, however, the applied voltage had two rates of rising (firstly, 15 kV/s and secondly, 1 kV/s). The applied voltage increased rapidly, up to 50% of the maximum set voltage, and then increased at a rate of 1 kV/s until breakdown occurred. This voltage application procedure reduced the duration of the test, while the number of samples recorded per second increased. During the experimentation, three signals have been recorded: the applied voltage, the leakage current, and the photomultiplier tube (PMT) signals. The needle electrodes of three different tip radius (P1 = 1 ± 0.1 µm, P2 = 5 ± 0.5 µm, and P1 = 10 ± 0.8 µm) are adopted to understand the influence of the tip radius. The inter-electrode gap distance is fixed to D = 10 mm. A view of the test cell is presented in Figure 1.

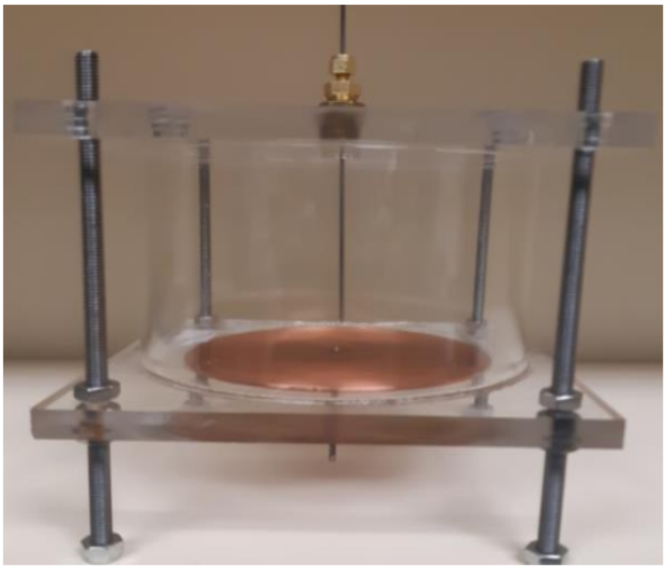

Figure 1. The view of a test cell.

3.2. Sample Preparation

The tests were carried out with new and aged MO, NE, and SE oils. Unused fluid samples were vacuumed down to reduce the initial moisture content: less than 5 ppm for mineral oil and less than 20 ppm for esters, which means approximately the same initial performance in terms of relative moisture content. For aging, one liter of each type of oil to be aged is transferred into a stainless-steel beaker. It is to be mentioned that pieces of copper strips (3 g/L) and cellulose kraft paper (1:20) are introduced into each beaker. The copper served as a metal catalyst and the presence of the paper simulated the real conditions of aging in transformers, making it possible to obtain decomposition products similar to those generated in oil from a real transformer. The oils were thermally aged at 115 °C for 1000 and 2000 h in a DKN900 type Yamato mechanical convection oven under open beaker conditions. The open beaker method allows some decay matters to be escaped from the aging cell [20]. However, continuous exposure to air (oxygen) accelerates the degradation process of the oil-paper insulation with high oxidation.

3.3. Sample Characterization

The thermal aging deteriorates the liquid dielectrics by breaking the covalent bonds. The recombination of free radicals favors the increase in viscosity, turbidity, and absorbance due to the presence of sludge and particles suspended in the oil. Figure 2 shows the results of turbidity and absorbance measured as per ASTM D6181 and ASTM D6802 respectively. The turbidity of SE is always lower than that of NE and MO, regardless of the duration of aging. The turbidity test result is in agreement with that obtained in [21]. The UV-VIS spectroscopy was used for measuring the absorbance and, so to speak, the relative amount of the dissolved decay products in the fluids at different wavelengths in UV and visible regions. The turbidity and absorbance to light increase with thermal degradation that leads to the suspension of colloidal and soluble particles in the volume of the liquid due to the thermal constraint breaking covalent bonds. It is noticed that absorbance to light increases with aging and, regardless of the duration of aging, the absorbance of NE is higher than that of MO and SE. The low absorbance values of SE indicate better resistance to thermal degradation compared to MO and NE.

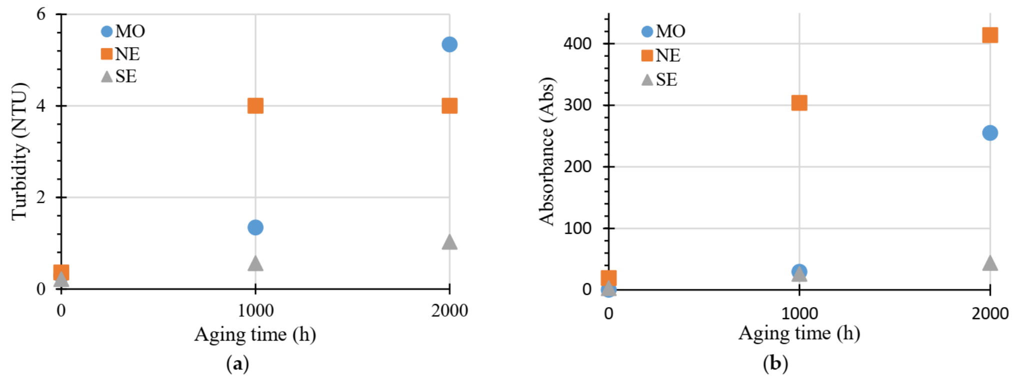

Figure 2. Liquid properties as a function of thermal aging: (**a**) Turbidity of fresh and aged liquids (**b**) Absorbance of fresh and aged liquids.

4. Results and Discussion

4.1. Delay Time (Δt)

The delay time ($\Delta t = t_{BSIT} - t_{PDPIT}$) is defined as the duration measured between the PD pre-inception time (PDPIT) and inception time of the streamers leading to the breakdown, i.e., breakdown streamer inception time (BSIT). The delay time is also referred to as the vulnerability period in this work. This is because it is the time during which ionization is onset and the avalanche building process is rapid in the liquid volume. The measure of this delay time actually reveals the time that different liquids can resist the development and propagation of the streamer in the bulk of the liquid. The delay time against thermal aging is presented in Figure 3. The duration of vulnerability is a random characteristic because it depends on two random characteristics (the time of occurrence of PDPIV and BSIV) that vary according to the type of dielectric liquid, the applied voltage, electrode geometry, etc. Regardless of the electrode tip and aging time, the vulnerability period (delay time) of MO is greater than that of the SE and NE. Except for fresh oils, the vulnerable period of SE is longer than that of NE. The vulnerable period of the fluids (MO, SE, and NE) is more than 8 s regardless of the aging duration and the tip of the electrode.

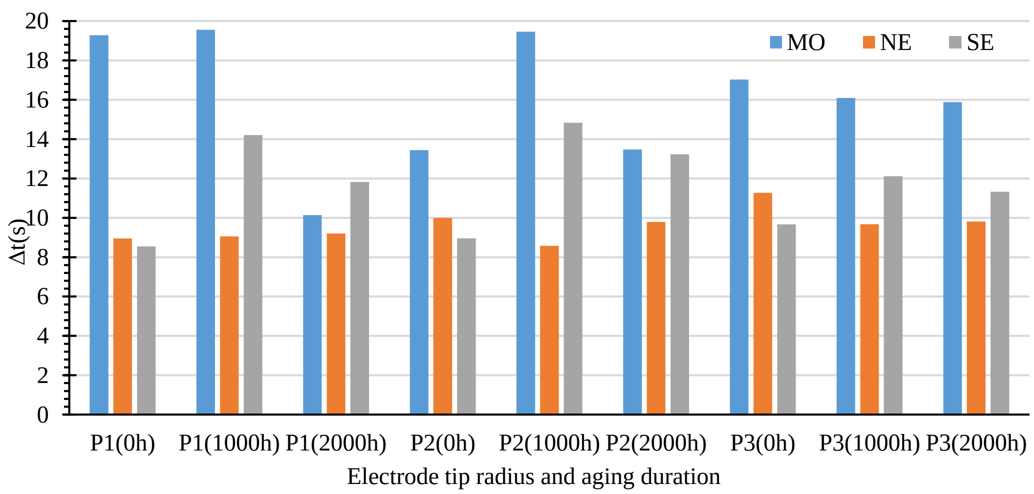

Figure 3. Delay time as a function of the electrode tip and aging time.

4.2. Pre-Breakdown Voltage

Dumitrescu et al. [22] observed a conduction current at voltages lower than the streamer inception voltage. This leakage current is referred to as streamer pre-inception current. In this paper, the streamers were studied under AC voltage, and the tests were carried out in the dark chamber. The leakage currents were measured by the acquisition system from the so-called streamer pre-inception voltage. Micro-sparks were observed propagating from the high voltage (HV) electrode to the plane electrode before the inception of the streamer, which led to the breakdown of the fluid dielectric. Figure 4 shows the pre-inception voltage for MO, NE, and SE. The pre-inception voltage of SE and NE is, in most cases, higher than that of the MO. The air bubbles, formed within the vicinity of the needle electrode, further develop to produce a string of globules. In the phase of pre-breakdown, gas bubbles are formed within the vicinity of the plane electrode and move towards the tip electrode. These strings of bubbles (chain of air bubbles) let pass the charges that are received as current pulses by the acquisition system adopted in the experimental setup of the present study. The appearance time of the first current pulses allows for measuring the pre-initiation voltage of the streamers in different insulating liquids.

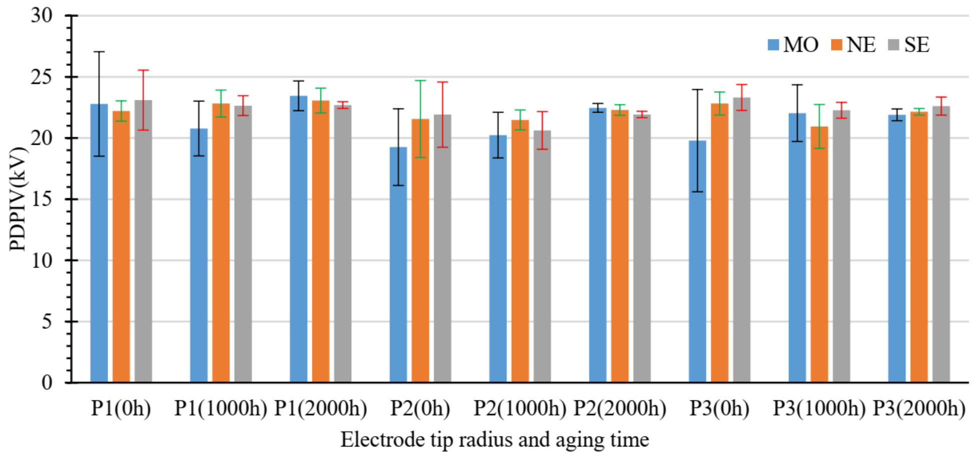

Figure 4. Pre-inception voltage as a function of the electrode tip and aging time.

4.3. Streamer Inception Voltage

The streamer inception voltage, or partial discharge inception voltage, is an important parameter in the selection of a liquid dielectric to be used in high-voltage apparatus.

Figure 5 shows the streamer inception voltage as a function of the electrode tip and aging time. For the same electrode tip, the streamer inception voltage decreases with aging time in MO. The streamer inception voltage in new MO is higher than that of new NE or SE, regardless of the electrode tip. This may be attributable to the low ionization resistance of the ester liquids. However, the streamer inception voltages of SE are mostly higher than that of the NE. The inception voltages appear to have much less difference in magnitude, and this is because the chosen needle tips have extremely small radii. It is believed that the inception of the ionization process arouses from the formation of an air bubble at the tip of the stressed electrode (needle tip here). Other than tip radius, the formation of this bubble depends on various factors, including hydrostatic pressure, temperature, and type of liquids. However, one may assume there to be significant differences in the magnitude of the inception voltage measured for a wide spectrum of the tip radii (small to high).

4.4. Breakdown Voltage

When a partial discharge is initiated in a liquid dielectric, an ionized channel is formed mostly with a string of globules. The conductivity of this channel depends on the voltage drop between the head of the partial discharge channel and the tip of the HV electrode. The conductivity of the channel is high if the rate of voltage drop is slow. The propagation velocity of the PD depends, mainly, on the nature of the dielectric liquid, electric field, and applied voltage. The voltage at which the discharge channel reaches the opposite electrode (grounded plain, in this study) is the "breakdown voltage". Figure 6 shows the average value and standard deviation of the breakdown voltages of the MO, SE, and NE oils. Similar to the case of lightning impulse breakdown voltage in [7], the AC breakdown voltage of MO is higher than that of SE and NE. Regardless of the tip of the needle electrode, the breakdown voltage of MO decreases with aging. The thermal aging seems to have more influence on the AC breakdown voltage of MO when compared to SE and NE. Within the range of the radius of curvature, this variable has little influence on the breakdown voltage.

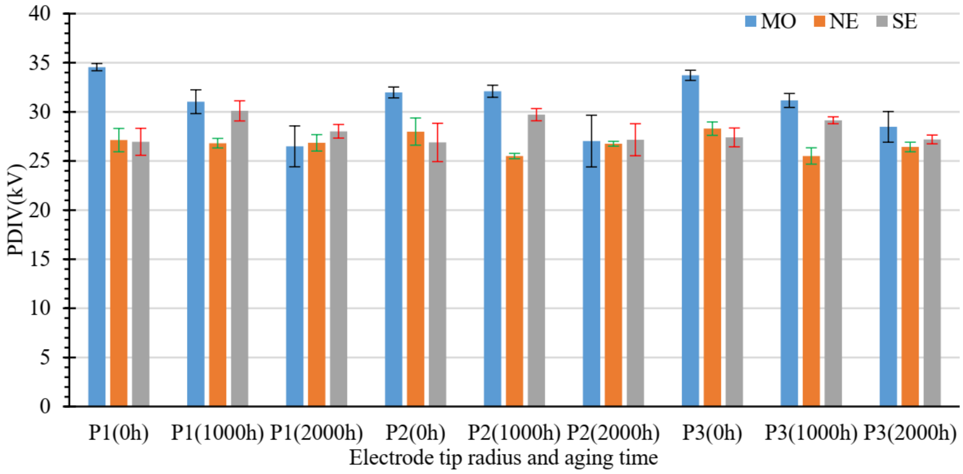

Figure 5. Partial discharge inception voltage as a function of the electrode radius and aging time.

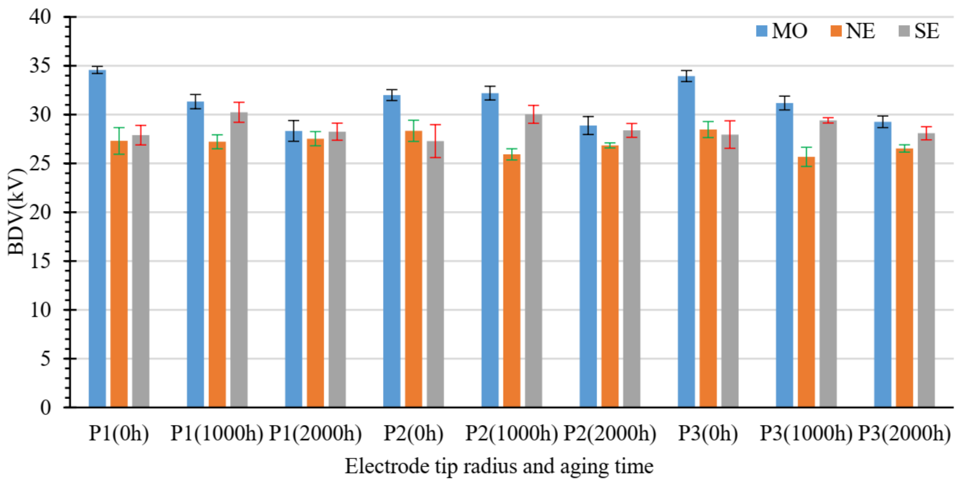

Figure 6. Breakdown voltage as a function of electrode tip and aging time.

4.5. Influence of Electric Field and Streamer Velocity

4.5.1. Electric Field

The electric field has an important role in the initiation and propagation of streamers. For the point-plane configuration, the electric field at the tip of the HV electrode is calculated by the hyperboloid approximation [21]. Figure 7 indicates that the computed electric field is strong at the tip, for a small radius of curvature P1 (1 µm), and decreases as the radius of curvature P3 (10 µm) increases. The tip electrodes with a small radius of curvature are more harmful because they locally amplify the electric field. An intense electric field at the HV electrode tip is responsible for the streamer inception and propagation. It should be noticed that, for a given electrode tip, the electric field in the oils studied is in the same order of magnitude, regardless of the duration of the thermal aging.

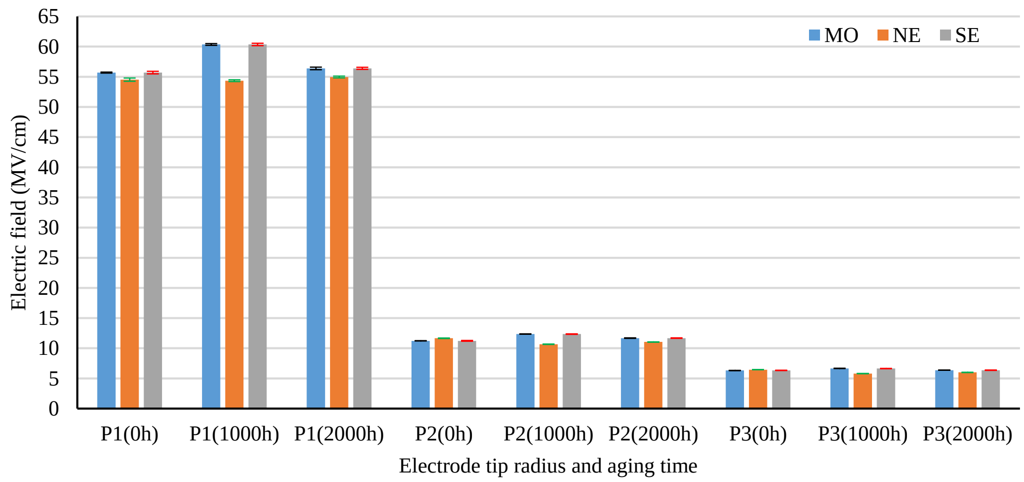

Figure 7. Electric field as a function of electrode tip and aging time.

4.5.2. Streamer Velocity

The streamers, reported in the present study, propagated in the slow mode (2nd mode about 2 km/s), which is due to the AC voltage application mode. The purpose of the electrical stress assessment is to determine the pre-inception and breakdown voltages of the dielectric liquids under study. Figure 8 shows the propagation velocity of the streamers for the tested oil samples. In Figure 8, the propagation velocity of streamers in new liquids is shown as a function of the tip electrodes. The propagation velocity of the streamers decreases with the increasing radius of the curvature of the tip electrode. The propagation velocity of the streamers also increases with the electric field increase. The large values of the standard deviation can be traced to the dispersion in the discharge propagation between the electrodes, significantly perturbed by generated space charges. The corona streamer transit time between electrodes and the streamers' average propagation velocities (*Vstr*), have been determined using the following equation

$$V_{srt} = \frac{D}{t}$$

with t = BDT−BSIT, where BDT is the time taken for the breakdown (derived from the leakage current signal), BSIT is the time when the first corona inception was obtained from signals recorded by the PM, and D is the inter-electrode distance.

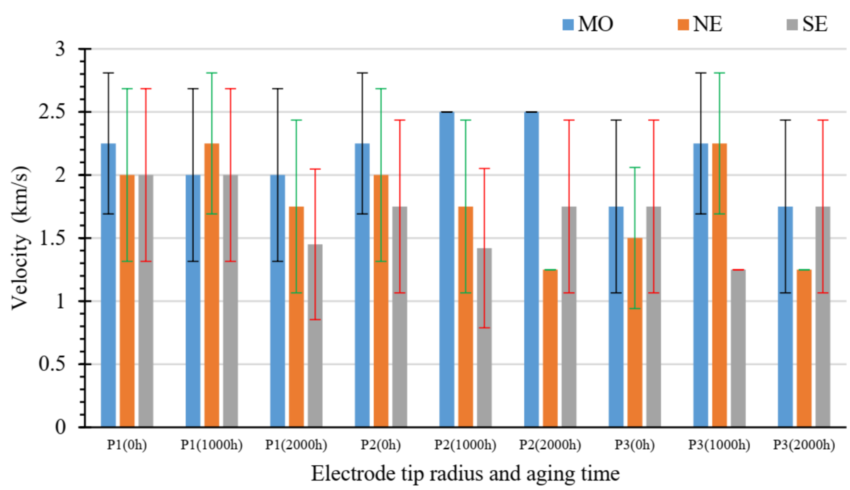

Figure 8. Streamer velocity as a function of electrodes tip radius and aging time.

5. Conclusions and Future Scope

In this paper, streamer characteristics such as propagation velocity, the electric field at the tip of the needle electrode, breakdown voltage, streamer inception voltage, and streamer pre-inception voltage have been investigated. The study was carried out under AC voltage, with a point-plane configuration for typical ester liquids and mineral oil. The main emphasis has been directed toward understanding the influence of thermal aging on the pre-breakdown and breakdown phenomena. The main findings of our investigation are summarized as follows:

- The duration of the delay time is high in mineral insulating oil and is generally more than 8 s for all the liquids regardless of the tip radius and age factor. The streamer's pre-inception voltages for NE and SE are slightly higher than that of the MO in most of the cases;
- The streamer inception voltage and breakdown voltages are almost identical at different tip radii, which is probably due to the extremely small tip radius adopted;
- The electric field at the electrode tip related to the streamer inception decreases with an increase in the radius of curvature. The electrodes with a small radius of curvature are detrimental to dielectrics;
- The streamers in the studied dielectrics propagate in the second mode (slow mode), and the propagation velocity seems to decrease with an increase in the radius of curvature. In other words, the average propagation speed of the streamers decreases with a reduction in the electric field at the HV electrode tip, during the inception of the streamers.

The needle-to-plate arrangement has the advantage of ease observation of streamer initiation. It is worth mentioning that the tip radii adopted for the present work are smaller (to cope up with the size of the decay particles). This could be a potential factor to not exhibit a significant difference among the measurements performed with different tips. The present experiments are carried out for typical synthetic and natural esters. The inferences are matching with the proof of concept available in the literature. However, further measurements and detailed correlations are to be investigated and reported. The same may also be compared with the measurements on a low pour point ester performed at different temperatures. Further investigations onto the mechanisms by which streamer propagates in the fluids, under moderately inhomogeneous fields with a wide variety of Schwaiger's factor are foreseen. Additionally, the creepage and puncture studies with pressboard are useful for design considerations. Furthermore, theoretical models for simulating pre-breakdown phenomena may allow a better understanding of the physical processes involved in the breakdown of insulating fluids. In addition, due to the increased occurrence of transients arising from variation in the operation of renewable energy sources and DC lines in the grids, investigations under DC, combined on non-standard waveforms, are required.

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References

1. Rozga, P.; Stanek, M. Characteristics of streamers developing at inception voltage in small gaps of natural ester, synthetic ester and mineral oil under lightning impulse. *IET Sci. Meas. Technol.* **2015**, *10*, 50–57. [CrossRef]
2. Rao, U.M.; Fofana, I.; Jaya, T.; Rodriguez-Celis, E.M.; Jalbert, J.; Picher, P. Alternative dielectric fluids for transformer insulation system: Progress, challenges, and future prospects. *IEEE Access* **2019**, *7*, 184552–184571.
3. Essam, A.A.-A. Optical observation of streamer propagation and breakdown in seed based insulating oil under impulse voltages. *Int. J. Phys. Sci.* **2014**, *9*, 292–301. [CrossRef]
4. Pompili, M.; Mazzetti, C.; Bartnikas, R. Comparative PD pulse burst characteristics of transformer type natural and synthetic ester fluids and mineral oils. *IEEE Trans. Dielectr. Electr. Insul.* **2009**, *16*, 1511–1518. [CrossRef]
5. Dang, V.H.; Beroual, A.; Perrier, C. Comparative study of statistical breakdown in mineral, synthetic and natural ester oils under AC voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1508–1513. [CrossRef]
6. Reffas, A.; Moulai, H.; Beroual, A. Creeping discharges propagating on natural ester oils/pressboard interface under AC and lightning impulse voltages. *IEEE Trans. Dielectr. Electr. Insul.* **2018**, *25*, 1814–1821. [CrossRef]
7. Liu, Q.; Wang, Z.D. Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2011**, *18*, 1908–1917. [CrossRef]
8. Chandrasekar, S.; Montanari, G.C. Analysis of partial discharge characteristics of natural esters as dielectric fluid for electric power apparatus applications. *IEEE Trans. Dielectr. Electr. Insul.* **2014**, *21*, 1251–1259. [CrossRef]
9. Rao, U.M.; Fofana, I.; Beroual, A.; Rozga, P.; Pompili, M.; Calcara, L.; Rapp, K.J. A review on pre-breakdown phenomena in ester fluids: Prepared by the international study group of IEEE DEIS liquid dielectrics technical committee. *IEEE Trans. Dielectr. Electr. Insul.* **2020**, *27*, 1546–1560. [CrossRef]
10. Dielectric Performance of Insulating Liquids for Transformers, CIGRE TB 856, WG D1.70, TF 3. 2021. Available online: https://e-cigre.org/publication/856-dielectric-performance-of-insulating-liquids-for-transformers (accessed on 21 December 2021).
11. Jayasree, T.; Rao, U.M.; Fofana, I.; Brettschneider, S.; Celis, E.M.R.; Picher, P. Pre-breakdown Phenomena and Influence of Aging Byproducts in Thermally Aged Low Pour Point Ester Fluids Under AC Stress. *IEEE Trans. Dielectr. Electr. Insul.* **2021**, *28*, 1563–1570. [CrossRef]
12. Lesaint, O. Prebreakdown phenomena in liquids: Propagation 'modes' and basic physical properties. *J. Phys. D Appl. Phys.* **2016**, *49*, 144001. [CrossRef]
13. Rozga, P. Using the light emission measurement in assessment of electrical discharge development in different liquid dielectrics under lightning impulse voltage. *Electr. Power Syst. Res.* **2016**, *140*, 321–328. [CrossRef]
14. Dang, V.-H.; Beroual, A.; Perrier, C. Investigations on streamers phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1521–1527. [CrossRef]
15. Haegele, S.; Vahidi, F.; Tenbohlen, S.; Rapp, K.J.; Sbravati, A. Lightning Impulse Withstand of Natural Ester Liquid. *Energies* **2018**, *11*, 1964. [CrossRef]
16. Lu, W.; Liu, Q.; Wang, Z.D. Pre-breakdown and breakdown mechanisms of an inhibited gas to liquid hydrocarbon transformer oil under negative lightning impulse voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 2809–2818. [CrossRef]
17. Perrier, C.; Beroual, A. Experimental Investigations on Insulating Ester, and Silicone Oils. *IEEE Electr. Insul. Mag.* **2009**, *25*, 6–13. [CrossRef]
18. Beroual, A.; Tobazeon, R. Prebreakdown Phenomena in Liquid Dielectrics. *IEEE Trans. Electr. Insul.* **1986**, *EI-21*, 613–627. [CrossRef]
19. Fofana, I.; Beroual, A. Predischarge Models in Dielectric Liquids. *Jpn. J. Appl. Phys.* **1998**, *37*, 2540–2547. [CrossRef]
20. Loiselle, L.; Rao, U.M.; Fofana, I.; Jaya, T. Monitoring colloidal and dissolved decay particles in ester dielectric fluids. *IEEE Trans. Dielectr. Electr. Insul.* **2020**, *27*, 1516–1524. [CrossRef]
21. Lu, W.; Liu, Q. Effect of cellulose particles on impulse breakdown in ester transformer liquids in uniform electric fields. *IEEE Trans. Dielectr. Electr. Insul.* **2015**, *22*, 2554–2564. [CrossRef]
22. Dumitrescu, L.; Lesaint, O.; Bonifaci, N.; Denat, A.; Notingher, P. Study of streamer inception in cyclohexane with a sensitive charge measurement technique under impulse voltage. *J. Electrost.* **2001**, *53*, 135–146. [CrossRef]