Prebreakdown and Breakdown Behaviour of Low Pour Point Dielectric Liquids Under Negative Lightning Impulse Voltage

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***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.**

***Index Terms*— Cold regions, Esters, Insulation oil, Streamers, Transformers.**

I. 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

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This work is co-sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC), Hydro-Québec (Grant No. RDCPJ513264-17), InnovÉÉ (R11-1707), and Polish National Agency for Academic Exchange (NAWA).

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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.

II. EXPERIMENTAL

A. 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.

B. 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 I.

TABLE I

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

C. 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 Fig. 1.

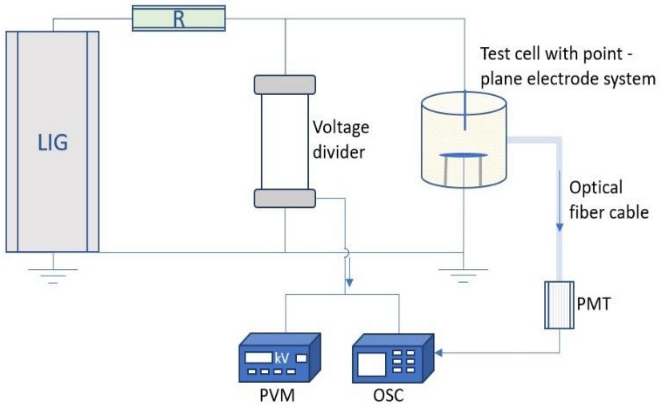


Fig. 1. Measurement setup used for testing: LIG – lightning impulse generator, R – current limiting resistor, OSC – digital oscilloscope, PMT - photomultiplier tube, PVM – peak value meter.

D. 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 Fig. 2.

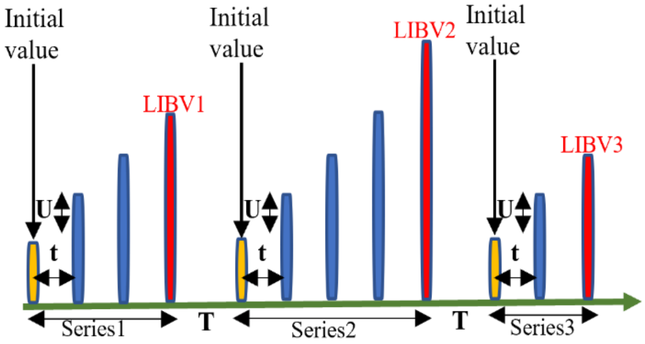


Fig. 2. The procedure adopted for LIBV measurement: LIBV1, LIBV2, LIBV3 – subsequent breakdown voltages, U – assumed voltage step, t – time lag between the subsequent LIs, T – time delay between measurement series.

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.

III. RESULTS AND DISCUSSIONS

A. 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 Fig. 3.

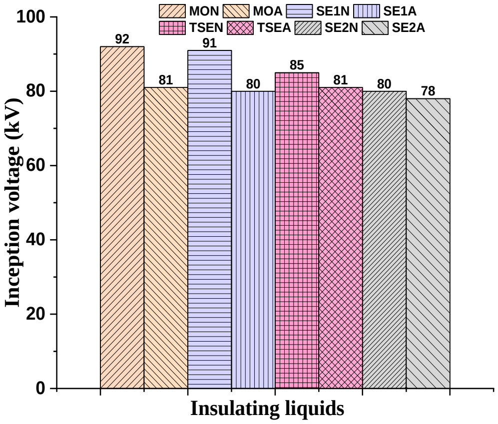


Fig. 3. Average streamer inception voltages for different test liquids under lightning impulses of negative polarity.

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.

B. 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 Fig. 4.

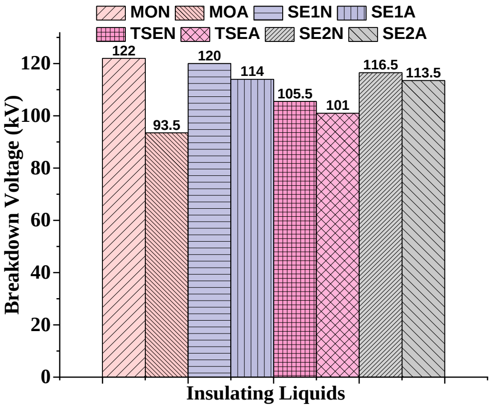
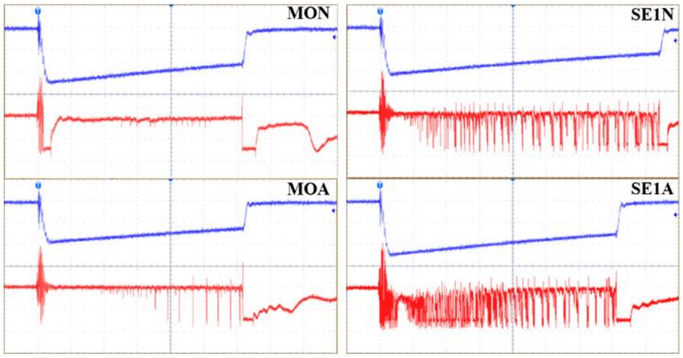


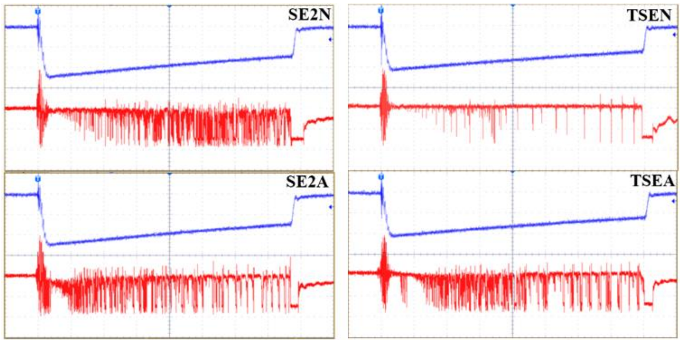
Fig. 4. Average lightning impulse breakdown voltage for different test liquids under negative polarity.

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 Fig. 5.



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



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

Fig. 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 II, while the probability distributions are shown in Figs. 6 and 7, respectively, for non-aged and aged liquids.

TABLE II
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

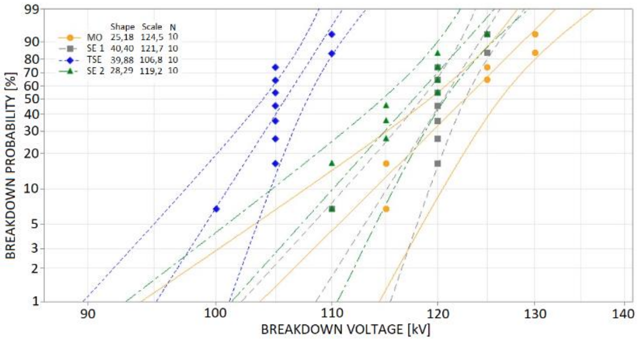


Fig. 6. Weibull distribution curves of the LIBV of the non-aged test liquids for point plane electrode system under negative polarity.

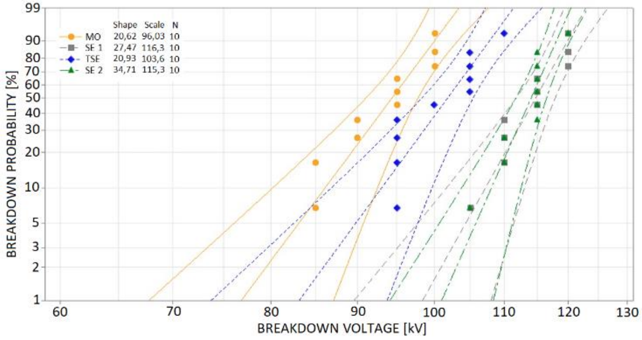


Fig. 7. Weibull distribution curves of the LIBV of the aged test liquids for point plane electrode system under negative polarity.

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.

C. 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 Fig. 8.

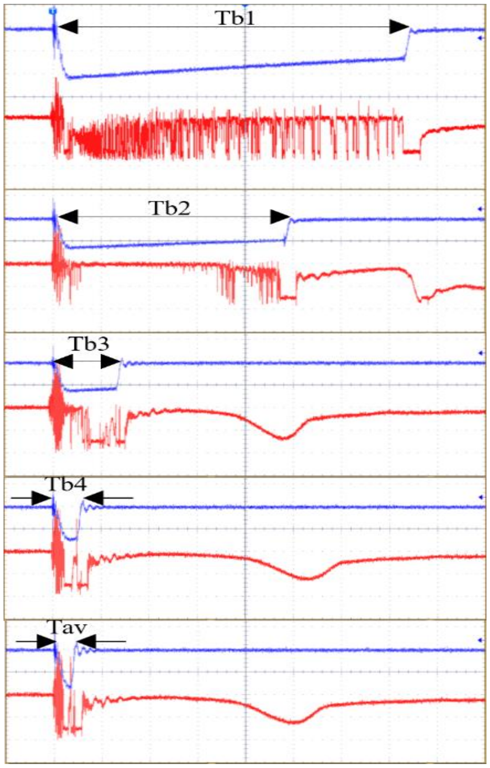
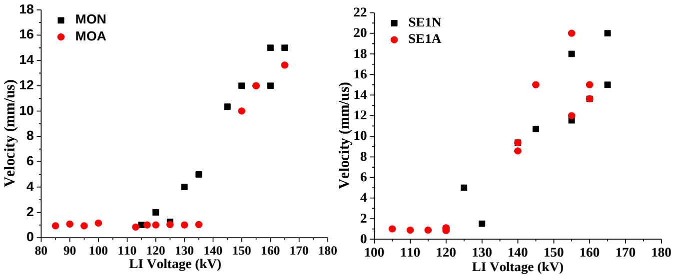


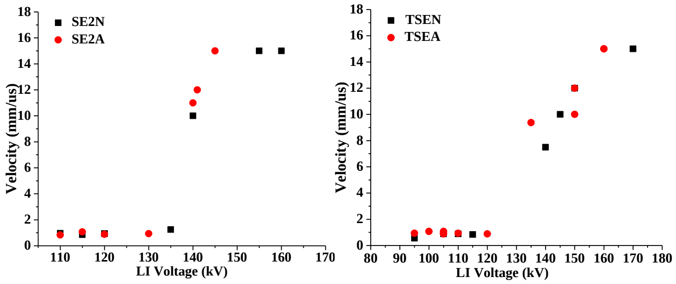
Fig. 8. Illustration of an example of the oscillograms recorded during the measurements performed for acceleration voltage: Tb1 - average LIBV of the test liquid; Tb2, Tb3, and Tb4 - subsequently reduced time to breakdown with increasing voltage, Tav - time to breakdown < 2 µs corresponding with the 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 Fig. 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

Fig. 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 Fig. 10.

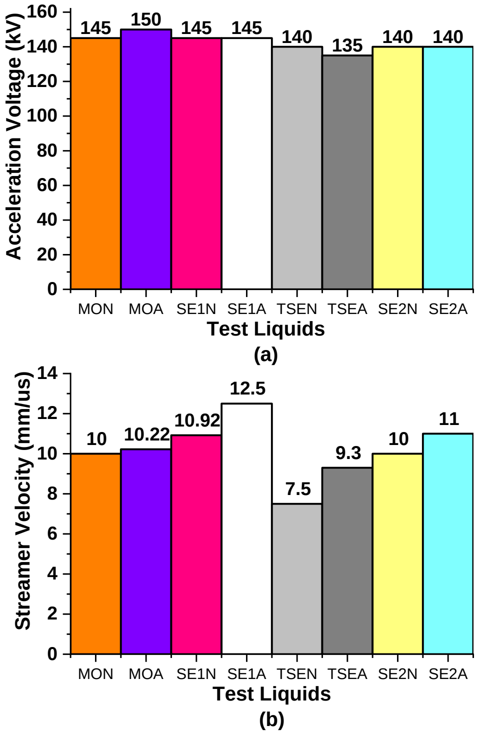


Fig. 10. Acceleration voltage and corresponding streamer velocities for all the test liquids.

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.

V. CONCLUSION

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

1) 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.
2) 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.
3) 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.
4) 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.
5) 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.

REFERENCES

[1] U. Mohan Rao et al., "Alternative Dielectric Fluids for Transformer Insulation System: Progress, Challenges, and Future Prospects," *IEEE Access*, vol. 7, pp. 184552-184571, 2019, doi: 10.1109/ACCESS.2019.2960020.

[2] T. Yang et al., "Low-Temperature Property Improvement on Green and Low-Carbon Natural Ester Insulating Oil," *IEEE Trans. on Dielect. and Elec. Insu.*, Vol. 29, no. 4, pp. 1459-1464, Aug. 2022, doi: 10.1109/TDEI.2022.3179224.

[3] L. Calcara, S. Sangiovanni and M. Pompili, "Standardized methods for the determination of breakdown voltages of liquid dielectrics," *IEEE Trans. on Dielect. and Elec. Insu*., vol. 26, no. 1, pp. 101-106, Feb. 2019, doi: 10.1109/TDEI.2018.007685.

[4] P. Rozga, F. Stuchala, T. Piotrowski, A. Beroual, "Influence of Temperature on Lightning Performance of Mineral Oil," *MDPI Energies*, vol. 15, no 3, pp: 1063, 2022, doi: 10.3390/en15031063.

[5] Q. Liu and Z. D. Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage," *IEEE Trans. on Dielect. and Elec. Insu.*, vol. 18, no. 6, pp. 1908-1917, Dec. 2011, doi: 10.1109/TDEI. 2011.6118629.

[6] U. Mohan Rao et al., "A review on pre-breakdown phenomena in ester fluids: Prepared by the international study group of IEEE DEIS liquid dielectrics technical committee," *IEEE Trans. on Dielect. and Elec. Insu.*, vol. 27, no. 5, pp. 1546-1560, Oct. 2020, doi: 10.1109/TDEI.2020.008765.

[7] P. Rozga and P. Tabaka, "Comparative analysis of breakdown spectra registered using optical spectrometry technique in biodegradable ester liquids and mineral oil," *IET Sci. Meas. Technol.*, vol. 12, no. 5, pp. 684-690, 2018, doi: 10.1049/iet-smt.2017.0229.

[8] T. Jayasree, U. Mohan Rao, I. Fofana, S. Brettschneider, E. M. R. Celis and P. Picher., "Pre-breakdown Phenomena and Influence of Aging Byproducts in Thermally Aged Low Pour Point Ester Fluids Under AC Stress," *IEEE Trans. on Dielect. and Elec. Insu.*, vol. 28, no. 5, pp. 1563-1570, Oct. 2021, doi: 10.1109/TDEI.2021.009600.

[9] A. Beroual and I. Fofana, "Discharge in Long Air Gaps – Modeling and Applications" IOP Publishing: http://iopscience.iop.org/book/978-0-7503-1236-3, June 2016.

[10] V-H. Dang, A. Beroual and C. Perrier, "Investigations on streamers phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage," *IEEE Trans. on Dielect. and Elec. Insu.*, vol. 19, no. 5, pp. 1521-1527, Oct. 2012, doi: 10.1109/TDEI.2012.6311496.

[11] *Standard Test Method for Oxidative Aging of Electrical Insulating Liquids by Open-Beaker Method*," ASTM std., ASTM D1934-20, 2021.

[12] W. Xin. "Partial discharge behaviours and breakdown mechanisms of ester transformer liquids under ac stress," Ph.D. Thesis, The University of Manchester, UK, 2011.

[13] CIGRE TB 157, "Effect of particles on transformer dielectric strength," WG 12.17, 2000.

[14] P. Rozga, M. Stanek, and B. Pasternak, "Characteristics of negative streamer development in ester liquids and mineral oil in a point-to-sphere electrode system with a pressboard barrier," *MDPI Energies*, vol. 11, no.5, pp: 1088, 2018, doi: 10.3390/en11051088.

[15] P. Rozga, T. Jayasree, U. Mohan Rao, I. Fofana, P. Picher, "Prebreakdown and Breakdown Phenomena in Ester Dielectric Liquids," Book Chapter in "*Alternative Liquids Dielectrics for High-Voltage Transformer Insulation Systems: Performance Analysis and Applications*," Wiley-IEEE Press, 147-183, 2022, doi: 10.1002/9781119800194.ch6.

[16] C. T. Duy, O. Lesaint, A. Denat and N. Bonifaci, "Streamer propagation and breakdown in natural ester at high voltage," *IEEE Trans. on Dielect. and Elec. Insu*., vol. 16, no. 6, pp. 1582-1594, Dec. 2009, doi:10.1109/TDEI.2009.5361578.

[17] O. Lesaint and G. Massala, "Positive streamer propagation in large oil gaps: experimental characterization of propagation modes," *IEEE Trans. on Dielect. and Elec. Insu.*, vol. 5, no. 3, pp. 360-370, June 1998, doi: 10.1109/94.689425.

[18] CIGRE TB, "Dielectric performance of insulating liquids for transformers," WG D1.70 TF3, 2021

[19] R. H. Fowler, L. Nordheim, "Electron emission in intense electric fields," *Proc. of the Royal Society of London*, Series A, Mathematical and Physical Character, No. 119, 781, pp.173-181, 1928, doi: 10.1098/rspa.1928.0091.

[20] W. Schottky, "Über kalte und warme Elektronenentladungen", *Zeitschrift für Physik*, vol. 14, no. 1, pp: 63-106, 1923.

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