Analysis of Breakdown Voltage of Low Pour Point Synthetic Ester Insulating Liquids under Lightning Impulse Voltage of both Polarities

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***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.**

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

I. 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

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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.

II. 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.

III. EXPERIMENTAL

A. 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 I.

TABLE I
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/m^3	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

B. 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 1.

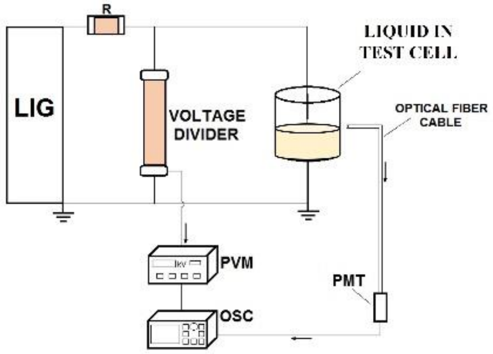


Fig. 1. Schematic of the measurement setup.

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 2.

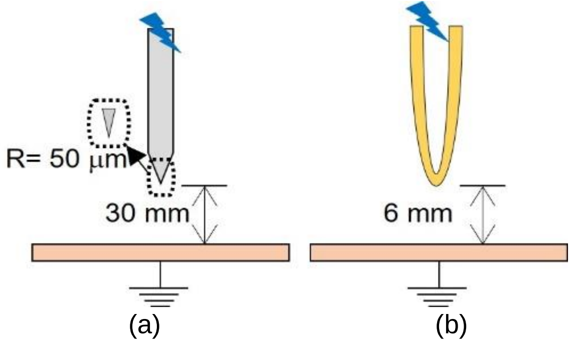


Fig. 2. The electrode configurations used for testing: a) Point-plane, b) U-Plane.

C. 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.

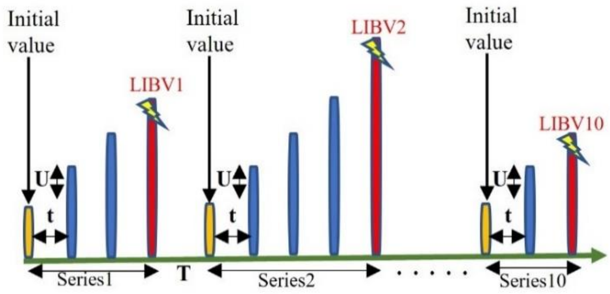


Fig. 3. Procedure of the LIBV measurement: LIBV1, LIBV2, LIBV10 – subsequent LIBVs (1, 2, .. 10), U – voltage step, t – time lag between two subsequent voltage steps (1 minute), T – time delay between subsequent measurement series (5 minutes).

IV. 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.

A. Negative Polarity

- *Point Plane Electrode*

The results of the lightning impulse breakdown under negative polarity for the point plane electrode system are presented in Table II. 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 4.

TABLE II

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

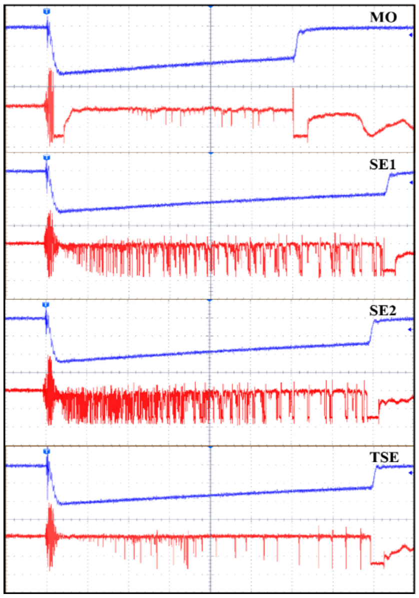


Fig. 4. Oscillograms of LIBV and light activity during the discharge process in various test liquids with point plane electrode configuration under negative polarity, t = 4 µs/div. V = 50 kV/div.

It is observed that the low pour point synthetic ester liquids (SE1 and SE2) have a 10 to 12% higher LIBDV 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.

- *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 III. 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 5.

TABLE III
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

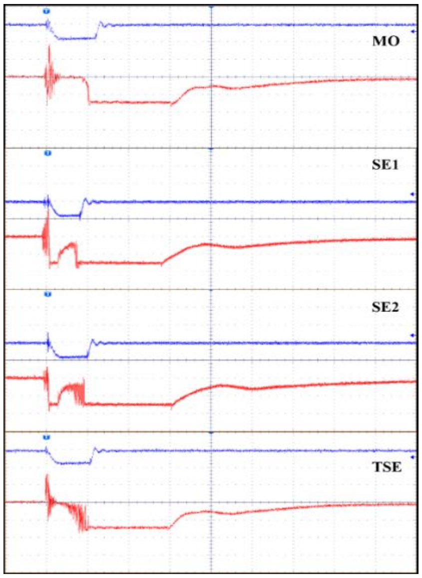


Fig. 5. Oscillograms of LIBV and light activity during the discharge process in various test liquids with U-plane electrode configuration under negative polarity, t = 4 µs/div., V = 100 kV/div.

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.

B. Positive Polarity

- *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. 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 6.

TABLE IV
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

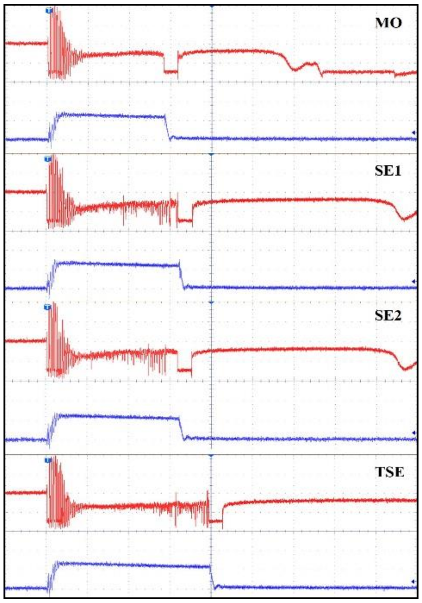


Fig. 6. Oscillograms of LIBV and light activity during the discharge process in various test liquids with point plane electrode configuration under positive polarity, t = 4 µs/div., V = 50 kV/div.

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.

- *U-Plane Electrode*

The results of the average lightning impulse breakdown under positive polarity for the U-plane electrode system are presented in Table V 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 7.

TABLE V
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

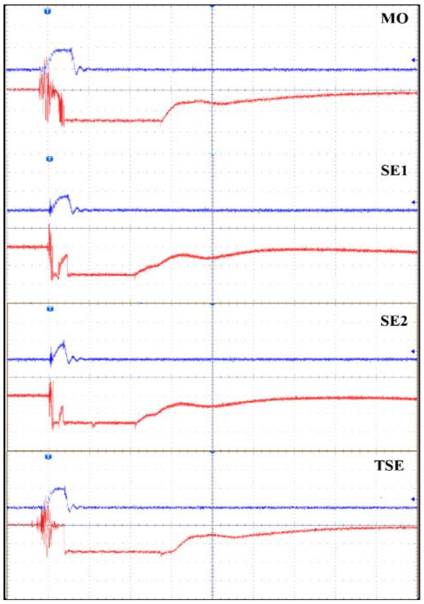


Fig. 7. Oscillograms of LIBV and light activity during the discharge process in various test liquids with U-plane electrode configuration under positive polarity, t = 4 μs/div., V = 100 kV/div.

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.

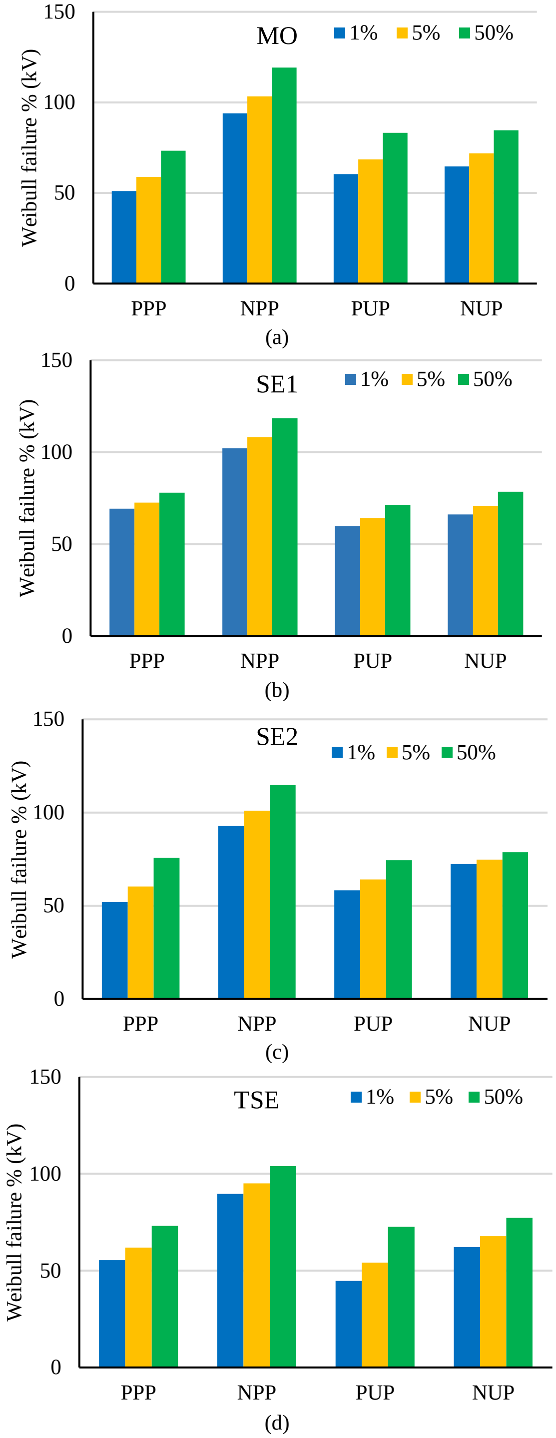
V. DISCUSSIONS

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 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.



(a)

(b)

(c)

(d)

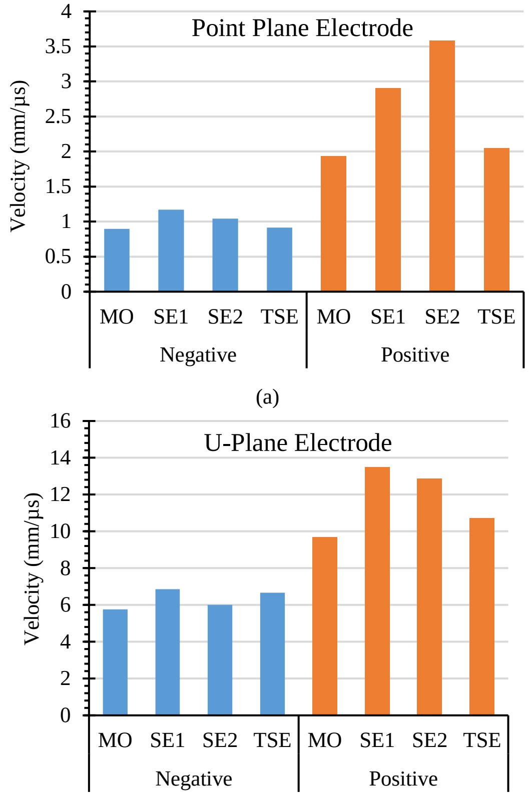
Fig. 8. Weibull failure probability percentages of the LIBV of the test liquids, (a). MO, (b). SE1, (c). SE2, (d). TSE.

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 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)

Fig. 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.

VI. CONCLUSION

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 LIBD 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. Also, comparing these results to the behaviour of silicon liquids [26], of course considering the opposite tendency for the pour points may add merit to the overall findings.

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