Breakdown and Withstand Strengths of Ester Transformer Liquids in a Quasi-uniform Field under Impulse Voltages

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ABSTRACT

This paper presents breakdown and withstand strengths of a synthetic ester, a natural ester and a mineral oil in a quasi-uniform sphere-to-sphere electric field under impulse voltages. The influences of impulse waveforms (lightning and switching), voltage polarities (positive and negative) and testing methods (rising-voltage, up-and-down and multiple-level) on the breakdown behaviour were investigated. The results indicated that breakdown voltages of both the ester liquids are comparable with those of the mineral oil under various test conditions. The withstand voltage at 1% breakdown probability was also obtained based on Weibull distribution fitting on the cumulative probability plot, which was built using the ~1000 impulse shots. It was found that the withstand voltages at 1% breakdown probability of the ester liquids are almost the same as that of the mineral oil. The results in this paper were further compared with other available test data in the literature. By comparing the performances between the ester liquids and the mineral oil, recommendations for insulation design were given to aid the application of ester liquids in high voltage large power transformers.

Index Terms — **Power transformer, breakdown voltage, withstand voltage, lightning, switching, quasi-uniform field, natural ester, synthetic ester and mineral oil.**

1 INTRODUCTION

APPLICATION of ester liquids in transformers has been extensively investigated in the past decade [1-8]. Both natural ester and synthetic ester have been considered owning to their better environmental performance and for some liquids their higher fire point. These liquids have already been widely used in distribution and traction transformers. In addition, with the progressing research and development activities, successful applications can be found in power transformers up to 240 kV. Nevertheless, it would still be of technical significance to adopt the ester liquids in large power transformers at higher voltage levels, e.g. 400 kV and above, due to the high cost and severe consequence of a factory test failure and the high level of safety and reliability required in service for these units.

Facing towards the applications in high-voltage power transformers, impulse strength of the ester liquids becomes more important than ever for the insulation design. Lightning impulse strength as basic insulation level (BIL) is commonly used as the criterion of insulation design for large power transformers. In addition, according to IEC standard 60076-3 [9], both lightning and switching impulse tests are usually required as factory routine tests for transformers with voltage rating higher than 170 kV.

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The majority of insulation materials inside a transformer, e.g. between turns, disks and windings, are exposed to a quasi-uniform electric field. Therefore any alternative insulation material to be considered should essentially have acceptable electrical strength in a quasi-uniform field. A great number of tests carried out by worldwide researchers have shown that AC breakdown voltages of the ester liquids are generally close to those of the mineral oils in a quasi-uniform field [3, 4, 10]. Compared with AC breakdown voltage that mainly indicates the oil conditions, e.g. moisture or particle contamination, impulse breakdown voltage tends to reveal the intrinsic property of a liquid.

Positive lightning (1.2/50 μs) breakdown voltages of a natural ester (rape-seed based oil) at gap distances from 5 mm to 15 mm in a plane-plane field geometry were reported in [11]. The volume of the test vessel was 150 litres. The breakdown voltage at each gap distance was taken as the average of 100 tests using rising-voltage method. The results indicated that the natural ester has similar breakdown voltages to the mineral oil.

Moving to larger gap distances, tests in a quasi-uniform field become more difficult, since larger volume of sample and longer time for sample preparation are required. Paper [12] reported the lightning (1.2/50 μs) breakdown voltages of a natural ester (Envirotemp® FR3, soy-seed based oil) in a quasi-uniform field at gap distances from 12 mm to 50 mm. The quasi-uniform field was achieved using a symmetric pair of electrodes made by the paper wrapped rectangular aluminium bars. Tanks with insulating liquid volume of 210 and 2,400 litres were used in the tests. Breakdown tests were conducted using rising-voltage method with three shots per step. Overall the lightning breakdown voltages of the natural ester are comparable to those of the mineral oil, with a maximum of ~17% reduction at the largest gap distance under both polarities. In addition, sample handling procedure (e.g. whether the sample is exposed to the air environment and if yes whether the vacuum is required afterwards) during the processing and testing was emphasized by the authors as an important factor which can influence the test results.

The most recent tests revealed the lightning (1.2/50 μs) impulse breakdown voltages of a natural ester (Envirotemp® FR3) at even larger gap distances from 50 mm to 150 mm using a specially designed bushing shield to plate electrode configuration [13]. Tests were carried out using up-and-down method with applied impulses from 25 to 42 shots in a very large tank containing 12,500 litres of the insulating liquid. The results indicated that breakdown voltages of the natural ester are close to those of the mineral oil at the investigated gap distances. Although the bushing shield to plate electrode configuration resembles more likely a slightly non-uniform field rather than a quasi-uniform field, comparing the results under negative and positive polarities, there is no polarity effect observed, so results using this field configuration are mentioned here and classified into the quasi-uniform field category.

Reviewing the published results on ester liquids impulse performance, the majority of the tests used lightning impulse voltage with either positive or negative polarity, and focused more on the natural ester than the synthetic ester. Various testing methods including rising-voltage method [14, 15], up-and-down method [16, 17] and multiple-level method [18] were utilized for impulse breakdown tests. In addition, due to the limitation of sample size, 50% breakdown voltage rather than withstand voltage was usually given. Yet, the withstand voltage at low breakdown probabilities e.g. 1% is actually more important for the insulation design of power transformers.

This paper presents the experimental results on impulse breakdown voltages of a natural ester, a synthetic ester and a mineral oil in a quasi-uniform electric field. The influences of impulse waveform, voltage polarity and testing methods on the 50% breakdown voltages are investigated. In addition, withstand voltages at 1% breakdown probability of both the natural ester and the synthetic ester are mathematically deduced based on the large amount of test data. Finally, the results in this paper are compared with other published relevant data at larger gaps, in order to obtain the relationship between breakdown/withstand strengths of the ester liquids and the applied gap distance.

2 EXPERIMENTAL DESCRIPTIONS

2.1 SAMPLE PREPARATION

Ester transformer liquids including the synthetic ester Midel 7131 and the natural ester FR3 were investigated in this paper and the mineral oil Gemini X was used as the benchmark. Descriptions of the liquids' basic properties were given in the previous publication [19].

The liquid samples were pre-processed through filtering, dehydrating and degassing to minimize the influence of impurity on the test results. Nylon membrane filter with pore size of 0.2 μm was used. The cumulative particle number larger than 5 μm of the filtered samples could be reduced to approximately 500 per 100 ml [20]. The filtered samples were dehydrated and degassed in a vacuum oven under 500 Pa (5 mbar) at 85 °C for 48 hours, and then a further 24 hours was given for the liquids to cool down to ambient temperature under vacuum condition. The water content of the processed samples was measured using Karl Fisher titration and the relative humidity was generally around 5%.

2.2 TEST SETUP

The test setup is shown in Figure 1. A cylindrical test cell with a liquid volume of 250 ml, was manufactured according to IEC 60897 "Methods for the Determination of the Lightning Impulse Breakdown Voltage of Insulating Liquids" [15]. The side wall of the test cell was made of transparent Perspex, which was then mounted on a nylon base. Brass sphere-sphere electrodes with a diameter of 12.5 mm were used to provide the quasi-uniform field at the gap distance of 3.8 mm.

A 10-stage Haefely impulse generator with a maximum voltage 2000 kV and energy 150 kJ was used to deliver the standard lightning impulse 1.2±30%/50±20% μs and the switching impulse 250±20%/2500±60% μs. The voltage waveform was measured by a high-voltage capacitive divider, and recorded by the DIAS 733 impulse analysis system.

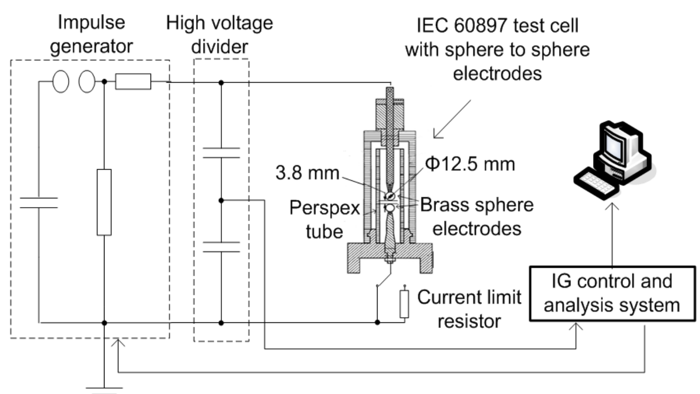


Figure 1. Sketch of test setup.

For the standard breakdown tests in section 3.1 and 3.2, the liquid sample and the pair of sphere electrodes were changed after each breakdown. However for the breakdown tests using various methods in section 3.3, in total hundreds of breakdowns were needed, so it was costly and time-consuming and thus impractical to change the liquid sample and electrodes after each breakdown. Alternatively, a current-limit resistor R_L (40 kΩ) was added in the circuit to limit the current of breakdown arc, further to protect the liquid sample and the electrodes. Verification tests showed that such a resistor had some effect on the actual voltage waveform applied on the test cell i.e. the front time was slowed down to approximately 2 μs without change of the tail time and the peak voltage reduction was less than 5%.

3 DETERMINATION OF BREAKDOWN VOLTAGES

3.1 INFLUENCE OF IMPULSE WAVEFORM

Both standard lightning impulse and switching impulse were applied in the breakdown tests to study the waveform influence. A 3.8 mm sphere-sphere gap was chosen according to ASTM D 3300 [14]. After filling the liquid sample, the test cell was degassed under vacuum for 20 minutes. Negative polarity voltage was used and it was increased step by step with step increment of 10 kV. At each voltage level, three shots were applied and the time interval between two consecutive shots was set to 60 seconds. 5 breakdown tests were carried out for each type of liquid under each type of impulse waveform.

The results of breakdown voltages of the ester liquids and the mineral oil under lightning impulse and switching impulse are given in Table 1 and Table 2 respectively. Mean lightning impulse breakdown voltage of Gemini X is the highest, 243.9 kV, followed by Midel 7131, 208.8 kV, and then FR3, 202.8 kV. Mean switching impulse breakdown voltage of Gemini X is again the highest, 184.3 kV, followed by FR3, 169.7 kV, and then Midel 7131, 169.2 kV. In addition to the breakdown voltage, time to breakdown of each breakdown was recorded. It was noted that the majority of breakdowns occurred around the peak voltage region of the applied impulse. However, interpretation of the time to breakdown in a quasi-uniform field is rather difficult, as there is a large component of initiation time that limits the calculation of streamer velocity.

Table 1. Negative lightning impulse breakdown voltages (LIBV) of ester liquids and mineral oil, d=3.8 mm, kV.

	Midel 7131	FR3	Gemini X
1st test	222.6	198.0	219.9
2nd test	180.0	195.5	209.0
3rd test	220.1	200.2	290.0
4th test	221.5	230.1	260.2
5th test	200.0	190.0	240.6
Mean LIBV (kV)	208.8	202.8	243.9
Standard deviation (kV)	18.6	15.7	32.4
Coefficient of variance	0.09	0.08	0.13

Table 2. Negative switching impulse breakdown voltages (SIBV) of ester liquids and mineral oil, d=3.8 mm, kV.

	Midel 7131	FR3	Gemini X
1st test	176.3	166.2	189.0
2nd test	160.0	160.0	181.0
3rd test	159.8	162.9	182.0
4th test	180.0	190.3	194.9
5th test	170.0	169.0	175.0
Mean SIBV (kV)	169.2	169.7	184.3
Standard deviation (kV)	9.2	12.0	7.7
Coefficient of variance	0.05	0.07	0.04

A cross comparison of impulse breakdown voltages between the lightning impulse and the switching impulse, and also between the ester liquids and the mineral oil is plotted in Figure 2. It is evident that impulse waveform has an influence on the breakdown voltage of a liquid. The shorter duration of the applied impulse waveform, the higher breakdown voltage measured. The 2nd mode streamer with a typical velocity of 1-2 mm/μs [21] is the most common streamer which leads to a breakdown in liquids. Suppose that the 2nd mode is applied at the short gap of 3.8 mm, the propagation of a streamer until it bridges the gap only requires approximately 1.9-3.8 μs; for a faster mode streamer, the propagation time would be even shorter. Accordingly, both the lightning and switching impulses can satisfy such short time streamer propagation without any obvious voltage decay. Therefore the different impulse waveforms mainly affect the streamer initiation in a quasi-uniform field. Compared with the lightning impulse, the longer duration of a switching impulse offers more chances to initiate a streamer and hence results in a statistically lower breakdown voltage.

In addition, both the ester liquids show relatively lower breakdown voltage than the mineral oil. Taking the mineral oil as the baseline, the percentage reductions of mean breakdown voltage for the ester liquids are approximately 15% under the lightning impulse, and 8% under the switching impulse.

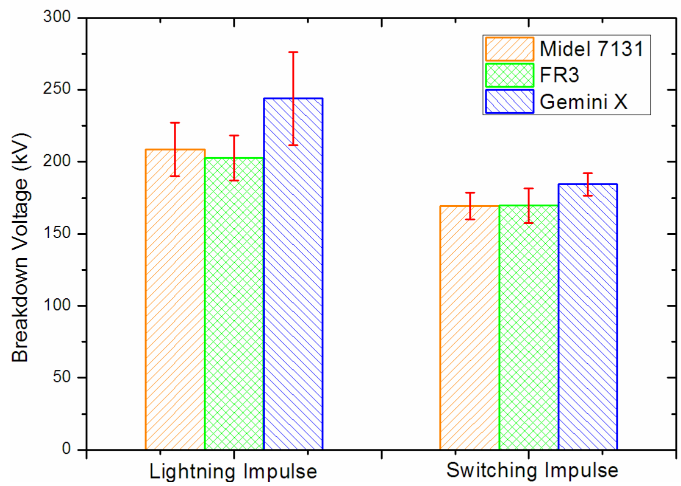


Figure 2. Influence of impulse waveform on mean breakdown voltage; vertical bars stand for one standard deviation, the same as following figures.

3.2 INFLUENCE OF VOLTAGE POLARITY

The polarity effect on breakdown voltages was investigated using the standard lightning impulse. The same electrode configuration and test procedure as in section 3.1 were applied. The results of breakdown voltages of the ester liquids and the mineral oil under positive lightning impulses are given in Table 3. Under positive polarity, mean lightning impulse breakdown voltage of Gemini X is also the highest, 236.0 kV, followed by FR3, 214.5 kV, and then Midel 7131, 205.7 kV.

Table 3. Positive lightning impulse breakdown voltages (LIBV) of ester liquids and mineral oil, d=3.8 mm, kV.

	Midel 7131	FR3	Gemini X
1st test	210.1	190.2	220.6
2nd test	219.9	239.9	239.9
3rd test	189.2	212.9	219.6
4th test	230.2	209.8	250.0
5th test	179.3	219.6	250.0
Mean LIBV(kV)	205.7	214.5	236.0
Standard deviation (kV)	21.1	17.9	15.1
Coefficient of variance	0.10	0.08	0.06

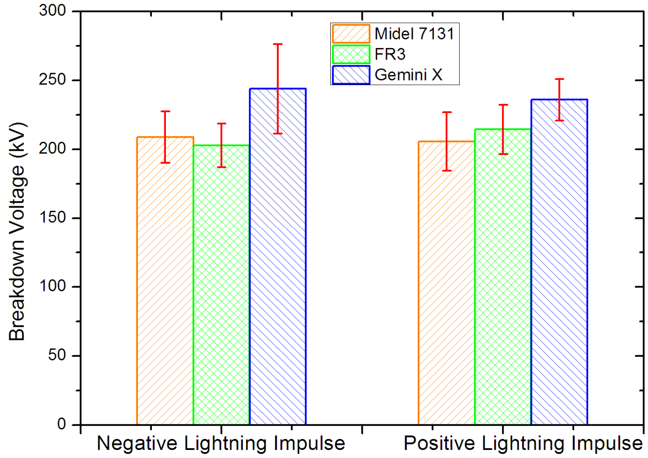


Figure 3. Influence of voltage polarity on mean lightning breakdown voltage.

As shown in Figure 3, the results of positive lightning breakdown tests are compared with those obtained under the negative polarity in section 3.1. In a divergent field, as the result of space charge issue, there is usually an obvious polarity effect that negative polarity results in a lower discharge inception voltage but a higher breakdown voltage than positive polarity. However, such a phenomenon is not expected in a uniform/quasi-uniform field due to the symmetric configuration. It is confirmed here that there is no polarity effect observed for both the ester liquids and the mineral oil. Overall, the mean lightning breakdown voltages of the ester liquids are slightly lower than those of the mineral oil under both positive and negative polarities.

3.3 INFLUENCE OF TESTING METHOD

Various testing methods including rising-voltage method [14, 15], up-and-down method [16, 17] and multiple-level method [18] are commonly used for the impulse breakdown tests. Each method has its own pros and cons, and also the validity range [20]. When comparing the impulse breakdown strength of various liquids, results based on different methods are likely to be different and hence could lead to a confusing situation. Therefore influence of testing method

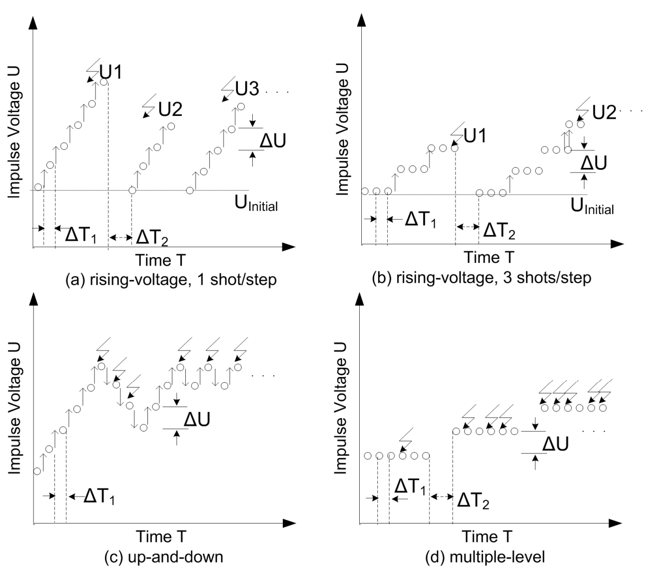


Figure 4. Illustration of various test procedures [20].

on the breakdown strength of the ester liquids and the mineral oil was examined using the standard lightning impulse.

After filling the liquid sample, the test cell was degassed under vacuum for 20 minutes. Negative polarity voltage was used. Both IEC 60897 and ASTM D 3300 [14, 15], standards for lightning breakdown tests of insulating liquid, adopt the rising-voltage method. The main difference between them is 1 shot per step for IEC standard while 3 shots per step for ASTM standard. Up-and-down method, proposed by Dixon and Mood, permits an estimation of 50% breakdown voltage, when the breakdown voltage is normally distributed [22]. It was initially applied in impulse breakdown tests of a gaseous gap that has a fast self-recovering character. Multiple-level method, also named as constant-voltage method, represents the 'classic' method for determining breakdown probability [22]. The illustrations of each type of method are shown in Figure 4 and the detailed descriptions of test procedures are given in the previous publication [20].

50% lightning impulse breakdown voltages of the ester liquids and the mineral oil using various testing methods are summarized in Table 4 and Figure 5. It is found that testing methods have a notable influence on the measured breakdown voltage. As for rising-voltage method, results using 3 shots per step procedure are lower than those using 1 shot per step procedure. Multiple-level method and rising-voltage method with 1 shot per step increasing rate provide the closest results, which are generally higher than those obtained using the other two methods.

Table 4. 50% lightning impulse breakdown voltages of ester liquids and mineral oil using various testing methods, d=3.8 mm, kV.

	Midel 7131	FR3	Gemini X
Rising-voltage (1 shot/step)	258.0	239.3	276.4
Rising-voltage (3 shots/step)	205.0	200.4	251.9
Up-and-down	223.2	212.9	232.8
Multiple-level	248.9	230.8	270.0

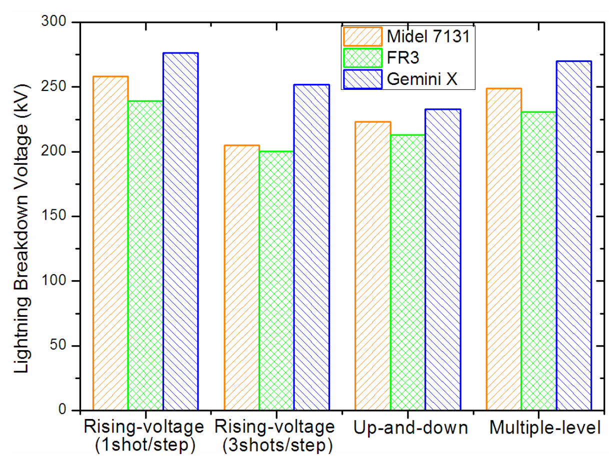


Figure 5. Comparison of 50% lightning breakdown voltages between ester liquids and mineral oil using various testing methods.

However, the testing methods which influence the absolute breakdown voltages do not affect the ranking of liquids for the aim of comparison. As indicated in Figure 5, the ester liquids always show lower 50% lightning breakdown voltage than the mineral oil no matter which kind of method is used. Considering the mineral oil Gemini X as the baseline, the percentage reductions of 50% breakdown voltages for the ester liquids are generally less than 20%.

4 DETERMINATION OF WITHSTAND VOLTAGES

4.1 METHOD TO DETERMINE WITHSTAND VOLTAGE

Withstand voltage is critically important for the insulation design of power transformers. Weibull distribution is usually used to fit the breakdown data, and then withstand voltage can be calculated based on the fitted curve with specific shape and scale parameters. The limitation of this method is the small sample size of the breakdown tests which could result in a large uncertainty of the deduced withstand voltage.

In the study of influence of testing methods in section 3.3, in total a large number of tests have been done for each type of liquid i.e. 1255 shots at various voltage levels for Gemini X, 912 shots for Midel 7131 and 639 shots for FR3. Ideally each single shot test should be an independent event and the obtained results should be independent of the test procedure. In practice, it is difficult to reach such ideal condition. However, some tactics can be used to minimize the influence of test procedure and maximally ensure the independence of each single shot test. In the present study, the following actions were taken: (i) all the liquid samples were filtered, dehydrated and degassed before the tests; (ii) the same 60-second time interval was used between two consecutive shots; (iii) a current-limit resistor was used to protect the electrodes and the liquid sample when breakdown occurred; (iv) after breakdown occurred, there was at least a 5-minute time interval until next shot and the liquid sample was regularly changed after about 10 breakdowns on average.

To maximally utilize the data obtained by using different test procedures, all of those data are compiled together as one set of data and sorted according to the applied voltage level. By counting the breakdown events, withstand and breakdown probabilities at each voltage level can be calculated. The results of both the ester liquids and the mineral oil are given in Table 5 to Table 7.

Table 5. Lightning breakdown probability at various voltage levels for synthetic ester Midel 7131.

Voltage Level (kV)	Applied Shots N	Withstand Probability	Breakdown Probability
125	36	1.000	0.000
130	30	1.000	0.000
140	63	1.000	0.000
150	62	1.000	0.000
160	60	0.967	0.033
170	53	0.981	0.019
180	50	0.940	0.060
190	46	0.978	0.022
200	73	0.877	0.123
210	46	0.935	0.065
220	89	0.831	0.169
230	42	0.810	0.190
240	56	0.857	0.143
245	10	0.600	0.400
250	29	0.483	0.517
255	10	0.800	0.200
260	57	0.509	0.491
270	11	0.364	0.636
280	65	0.077	0.923
290	2	0.500	0.500
300	21	0.048	0.952
310	1	0.000	1.000

Table 6. Lightning breakdown probability at various voltage levels for natural ester FR3.

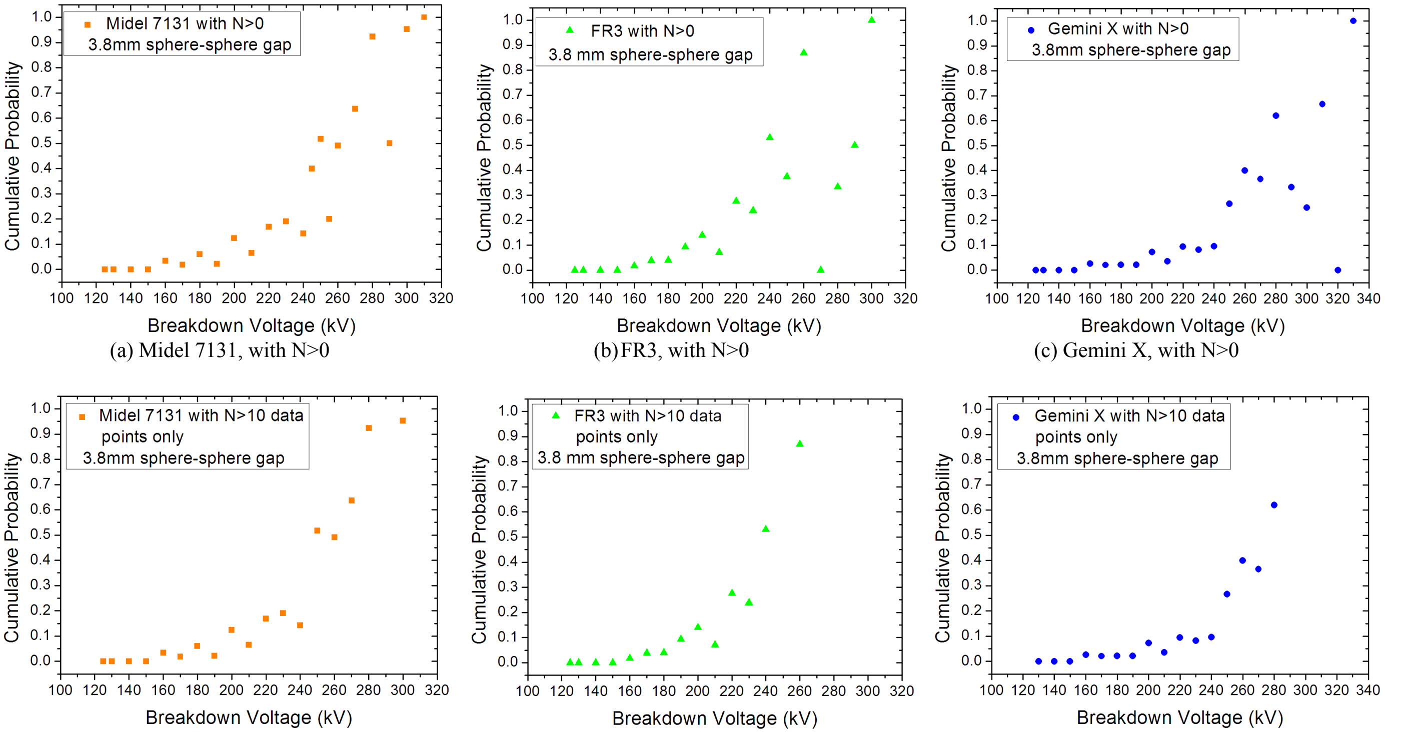
Voltage Level (kV)	Applied Shots N	Withstand Probability	Breakdown Probability
125	33	1.000	0.000
130	30	1.000	0.000
140	58	1.000	0.000
150	58	1.000	0.000
160	56	0.982	0.018
170	52	0.962	0.038
180	50	0.960	0.040
190	43	0.907	0.093
200	57	0.860	0.140
210	28	0.929	0.071
220	47	0.723	0.277
230	21	0.762	0.238
240	66	0.470	0.530
250	8	0.625	0.375
260	23	0.130	0.870
270	3	1.000	0.000
280	3	0.667	0.333
290	2	0.500	0.500
300	1	0.000	1.000

Table 7. Lightning breakdown probability at various voltage levels for mineral oil Gemini X.

Voltage Level (kV)	Applied Shot N	Withstand Probability	Breakdown Probability
125	9	1.000	0.000
130	45	1.000	0.000
140	83	1.000	0.000
150	82	1.000	0.000
160	78	0.974	0.026
170	96	0.979	0.021
180	95	0.979	0.021
190	93	0.978	0.022
200	96	0.927	0.073
210	85	0.965	0.035
220	85	0.906	0.094
230	73	0.918	0.082
240	94	0.904	0.096
250	60	0.733	0.267
260	80	0.600	0.400
270	41	0.634	0.366
280	42	0.381	0.619
290	9	0.667	0.333
300	4	0.750	0.250
310	3	0.333	0.667
320	1	1.000	0.000
330	1	0.000	1.000

At some voltage levels especially the high voltage levels, the number of applied shots is very limited that leads to a large variation of the cumulative probability distribution, as show in Figure 6a, 6b and 6c. Since it is suggested in [23] that at least 10 shots should be applied at each voltage level to calculate the breakdown probability, all the data are further processed using the same criterion that data with applied shots $N \leq 10$ are filtered out, as shown in Figure 6d, 6e and 6f. It is understandable that the processed data represent a much more reasonable distribution of the cumulative probability.

Weibull distribution was used to fit the cumulative breakdown probability data and further to calculate the breakdown voltage at low probabilities e.g. 1% that is also called withstand voltage. The cumulative probability of



(a) Midel 7131, with N>0 (b) FR3, with N>0 (c) Gemini X, with N>0

(d) Midel 7131, with N>10 (e) FR3, with N>10 (f) Gemini X, with N>10

Figure 6. Cumulative probability plot for lightning impulse withstand voltage calculation.

Weibull distribution *F(x)* at the voltage level *x* is given as follows:

$$F(x) = 1 - e^{-(\frac{x}{\beta})^{\alpha}} \quad (1)$$

where, α is the shape parameter,
β is the scale parameter.

To simply obtain the shape and scale parameters, the cumulative distribution function (1) can be linearised according to the following transformation:

$$\ln(\ln(\frac{1}{1-F(x)})) = \alpha\ln(x) - \alpha\ln(\beta) \quad (2)$$

Therefore the processed data for each type of liquid in Figure 6d, 6e and 6f are reproduced together in Figure 7 using a Weibull-plot scale. Based on the linear fitting of the data in Figure 7, both the scale and shape parameters of Weibull distribution are obtained and given in Table 8. Knowing the specific shape and scale parameters of Weibull function, the withstand voltage at low breakdown probabilities e.g. 1% can be easily deduced. As indicated in Table 8, the 50% breakdown voltages of the ester liquids are lower than that of the mineral oil which is consistent with previously drawn conclusions using various testing methods. Moving down to the lower breakdown probability, the difference between the ester liquids and the mineral oil becomes smaller. As for withstand voltages at 1% breakdown probability, they are 153.1 kV and 151.0 kV for Midel 7131 and FR3 respectively, which are slightly lower than that of the mineral oil 156.7 kV.

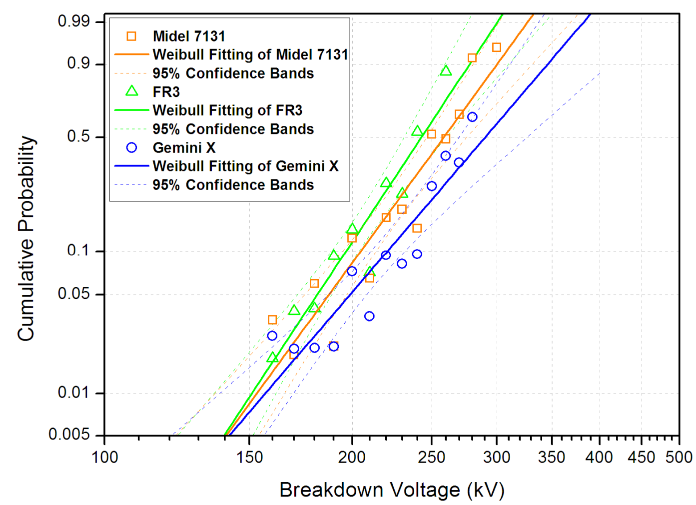


Figure 7. Cumulative probability versus breakdown voltage for lightning impulse withstand voltage calculation using Weibull fitting.

Table 8. Lightning withstand voltages of ester liquids and mineral oil, d=3.8 mm, kV.

		Midel 7131	FR3	Gemini X
Weibull fitting parameters	Scale	270.47	252.95	306.04
	Shape	8.08	8.91	6.87
	R^2	0.878	0.906	0.852
Breakdown voltage at 50% breakdown probability (kV)		258.5	242.8	290.1
Withstand voltage at 1% breakdown probability (kV)		153.1	151.0	156.7

4.2 COMPARISON WITH LARGE GAP TESTS

The results in the present study at a 3.8 mm sphere-sphere gap were then compared with those results at large gap distances up to 150 mm in the literature [12, 13], as shown in

Figure 8, all of these results were conducted under negative 1.2/50 µs lightning impulse voltage. It was also noted that the same natural ester liquid was used in the studies shown in Figure 8.

50% breakdown strength (50% breakdown voltage divided by the gap distance) 63.9 kV/mm and 76.3 kV/mm for the natural ester and the mineral oil respectively and withstand strength at 1% breakdown probability (withstand voltage at 1% breakdown probability divided by the gap distance) 39.7 kV/mm and 41.2 kV/mm for the natural ester and the mineral oil respectively, are plotted in Figure 8 to represent the results of the present study.

Tests at gap distances from 10 mm to 50 mm were done using a symmetric pair of electrodes made by the paper wrapped rectangular aluminium bar [12]; tests at gap distances from 50 mm to 150 mm were carried out using bushing shield disk to plate electrodes [13]. The Weidmann design curve for lightning impulse stress is obtained using the AC discharge inception design curve [24] multiplied by the design insulation level factor of 2.5 [12]. (The AC discharge inception design curve was obtained using degassed mineral oil with consideration of oil gaps adjacent to the windings [24]).

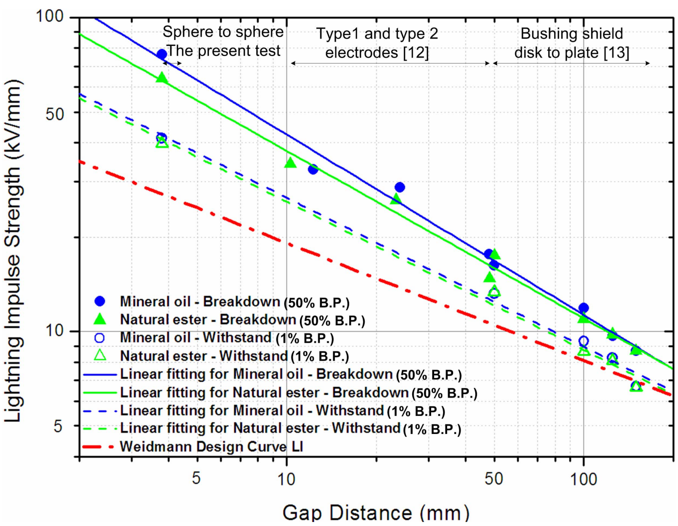


Figure 8. Negative lightning impulse strengths of ester liquids and mineral oil versus gap distances in quasi-uniform fields, the data at gaps from 10 mm to 150 mm are obtained from the literature [12, 13]. B.P. stands for breakdown probability.

As shown in Figure 8, the present results at the small gap distance of 3.8 mm match well those results at large gaps. It is indicated that lightning impulse strengths for both breakdown and withstand decrease with the increase of gap distance in a linear relationship under logarithm scale. Therefore the power law function can be used to fit the data, and the deduced empirical formulas for lightning impulse strength E (kV/mm) at the gap distance d (mm) are given as follows:

$$E_{\text{Mineral Oil}-\text{breakdown (50\%B.P.)}} = 159.02 \times d^{-0.57} \quad (3)$$

$$E_{\text{Natural Ester}-\text{breakdown (50\%B.P.)}} = 128.27 \times d^{-0.53} \quad (4)$$

$$E_{\text{Mineral Oil}-\text{withstand (1\%B.P.)}} = 79.48 \times d^{-0.47} \quad (5)$$

$$E_{\text{Natural Ester}-\text{withstand (1\%B.P.)}} = 76.84 \times d^{-0.47} \quad (6)$$

Generally the withstand strengths at 1% breakdown probability are lower than 50% breakdown strengths and the decreasing trends with gap distance for both of them are almost in parallel. Comparing the natural ester and the mineral oil, it is remarkable that the negative lightning impulse strengths of natural ester stay close to those of mineral oil in a quasi-uniform field at the gap distances up to 150 mm. Importantly, the withstand strengths of both the natural ester and the mineral oil are higher than the Weidmann design curve, except for a little overlapping at the gap distance of 150 mm. As there is no polarity effect expected in such a quasi-uniform field, the conclusion based on negative polarity tests should be valid for positive polarity as well.

5 DISCUSSIONS ON THE APPLICATION OF ESTER LIQUIDS

The previous studies in a divergent field [6, 19, 25-27] revealed that the ester liquids have evidently lower impulse breakdown voltages, especially at large gaps, than the mineral oil, because streamers in the ester liquids propagate faster and further than in the mineral oil at the same voltage level. However streamer inception voltages of the ester liquids are comparable with that of the mineral oil.

A breakdown event in liquids generally involves two processes including initiation and propagation of a streamer. Breakdown mechanism is closely related to the electric field of the applied electrode geometry. As for non-uniform fields with a high inhomogeneity factor e.g. at a long point-plane gap, the breakdown is dominated by the streamer propagation; and for uniform fields or quasi-uniform fields with a low inhomogeneity factor e.g. at a short sphere-sphere gap, the breakdown is dominated by the streamer initiation [21].

The present study incorporating the data from literature shows that the ester liquids have essentially comparable lightning impulse breakdown strengths to the mineral oil in a quasi-uniform field at various gap distances. This conclusion conforms to the theory of breakdown mechanism and the observation of inception voltages in the divergent field.

Considering lightning impulse strength is commonly used as the criterion of insulation design for large power transformers, and the majority of insulation materials inside a transformer are experiencing a quasi-uniform electric field, the observation of the ester liquids' comparable lightning impulse strengths with the mineral oil in a quasi-uniform field certainly moves the application of ester liquids in power transformers a step forward. It implies that the designed operation stresses and therefore the basic size and configuration of an ester-filled transformer can be similar to that of a mineral oil filled unit.

Nevertheless, additional considerations should be given to ester- filled power transformers. First, since streamers in the ester liquids, once incepted, propagate faster and further, the avoidance of streamer inception is likely to be even more important for design and construction of an ester-filled power transformer so as to avoid breakdown, particularly under the factory test stresses; second, to compensate for the lower breakdown strength of the ester liquids in a large divergent field gap, additional pressboard barriers (in a direction perpendicular to the field) may need to be added as partitions in large oil gaps in an ester-filled power transformer.

6 CONCLUSIONS

Impulse breakdown behaviours of two types of ester transformer liquid in a quasi uniform electric field were investigated by considering the influences of impulse waveform, voltage polarity and testing method. The results indicated that the switching impulse breakdown voltages are lower than the lightning impulse breakdown voltages for both the ester liquids and the mineral oil. There is no polarity effect for the impulse breakdown tests in a quasi-uniform field. Testing methods including rising-voltage method, up-and-down method and multiple-level method, have notable influence on the absolute breakdown voltages, but do not affect the ranking of liquids for the purpose of comparison. Overall, the ester liquids have comparable impulse breakdown strengths to the mineral oil.

By using Weibull distribution fitting to the probability curve produced by all the thousands of shots, withstand voltages at 1% breakdown probability of the ester liquids were deduced, which were close to that of the mineral oil.

Incorporating the published results in the literature, it was concluded that lightning impulse strengths of ester liquids for both breakdown and withstand, are comparable to those of the mineral oil at various gap distances in a quasi-uniform field. Therefore the designed operation stresses and the basic size and configuration of an ester-filled transformer can be similar to that of a mineral oil filled unit. However further design considerations e.g. avoiding streamer inception and partitioning the large oil gaps with additional pressboards, need to be made in order to cope with the inferior performance of the ester liquids in a divergent field.

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