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Lightning Impulse Breakdown Voltage of Rice Bran Oil for Transformer Application

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Abstract: Transformer oil does not only serve as an insulating liquid, but also in removing heat from the windings and cores. Mineral oil (MO) has been widely used in transformers for more than 150 years. Recently, researchers have attempted to search for alternative insulating oils due to the possibility that MO will run out in the future together with the concern on fire safety and environmental pollution. Among the potential oils is rice bran oil (RBO). This work presents the studies of the lightning impulse (LI) of RBO behavior under various electric fields, gap distances and testing methods. The electrical performances of LI tests show that RBO and Palm Oil (PO) have lower LI breakdown voltage than MO under both uniform and non-uniform electric fields. However, the difference in LI breakdown voltages between RBO, PO and MO are slightly small which is less than 20%. In addition, there is no significant effect in the various testing methods under both uniform field and non-uniform field where the percentages of difference are less than 12% and 8% respectively. The data of LI breakdown voltage were statistically analysed to predict the withstand voltage and 50% breakdown voltage of oil samples by using Weibull distribution. The Weibull distribution of MO, PO and RBO has well fit with the fitting line. Finally, the relationship between LI voltages under a non-uniform field with various parameters of PO and RBO was obtained and proposed. From this work, it can be concluded that RBO shows promising results to be considered as an alternative to MO in transformer applications.

Keywords: rice bran oi; transformer liquid insulation; vegetable oils; lightning impulse breakdown voltage; power transformer and dielectric material

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1. Introduction

Transformer is one of the most expensive and critical components in electrical power system transmission and distribution. A transformer failure could be a very catastrophic event which may cause severe disruption and complete blackout of the system [1,2]. Based on the literature [1–4], the post-failure analyses of transformers showed that insulation failure is a contributor to transformer failures. Oil and paper have been used as insulation materials for power transformers over the past centuries [5,6]. Transformer oil is used to fill the void in the paper insulation and also fill the gaps between components in the transformer tank which increases the dielectric strength of the insulation system. The oil does not only serve as an insulating liquid but also as a heat remover from the windings and cores [5,6]. The heat is a result of the losses from the transformer windings and cores. The oil is also used as an indicator in monitoring the condition of a power transformer.

Mineral oil (MO) has been widely used in power transformers for more than 150 years. MO originated from petroleum, and it has several attractive electrical and thermal properties for transformer application. Among the advantages of using MO are it is low cost, widely available and it has low viscosity. It is used in oil-filled transformers of all voltage ratings, from distribution to transmission level. However, MO also has some undesirable properties which affect oil performance. Somehow, MO is poorly biodegradable and can cause serious environment pollution to the soil and waterways if serious spills occur during incidents such as transformer explosion [6–9]. Also, MO is a combustible liquid with a flash and fire point of 170 °C and transformer fires may unavoidably occur. Hence, the concern of fire safety and the inability to comply with environmental laws have encouraged the search for alternative dielectric fluids in power transformers.

In recent years, vegetable oils were introduced as an alternative to the MO. Vegetable oils have a higher flash and fire point than MO and are biodegradable which reduced environmental impact and are non-toxic to organisms and humans [6–9]. Based on previous studies, vegetable oils are 97–99% biodegradable for 21 days of testing according to ASTM D-5864 whereas MO is only 30% biodegradable for similar period [10,11]. Besides that, their superior thermo-physical and enhanced dielectric properties help to speed up the preference in using vegetable oils as transformer oil. However, vegetable oils also have limitations and the most critical is oxidation stability for long term application. Vegetable oils are highly susceptible to oxidation which limits its application in free breathing transformer. Therefore, exposure to oxygen and moisture must be minimized and this can be achieved by hermetic sealing design of transformer against ambient air. For free breather transformer, oxidation inhibitors and metal passivators probably will need to be added to vegetable oil. Besides that, modifying chemical structures of vegetable oil by transesterification proses of vegetable oils is another way that could overcome the oxidation problem in transformer.

Before vegetable oils can be accepted as an alternative to MO, they must be safe, economical and offer a high standard of electrical properties over the transformer lifespan. Recently, extensive works were carried out to investigate the suitability of vegetable oils as the alternative to MO [12–18]. The studies evaluated dielectric properties, physical and chemical performances under different conditions and ageing properties.

Among the vegetable oil that is attractive and could be proposed is Rice Bran Oil (RBO). RBO is extensively used in Asian countries [19]. RBO as a by-product of rice milling is obtained from the outer layer of the brown rice kernel accounting for 6–8% of the paddy rusk. The global paddy rusk production was 741 million tons and this huge amount of production resulted in more than 50 million tons of RBO in 2014 [19,20]. RBO is widely used for various purposes such as cooking, fuel, and biodiesel [21,22] but not in transformer until now. The advantage of RBO is it has good oxidation stability which is good for transformer application [22]. In 2016, S. Senthil Kumar investigated RBO for the ability to be used as an alternative transformer oil. The initial study showed that the AC breakdown voltage of RBO has comparable performance to other natural esters [21–26]. This finding is supported by Mardiah [23] in which the breakdown voltage of RBO is having the highest breakdown voltage when compared to MO and PO. Other findings observed that RBO has promising dielectric and chemical properties among other vegetable oils [19–24]. Another advantage of RBO is the cost and the availability of RBO is like mineral oil. This is due to an economic and efficient method for recovery the oil from paddy husk [25].

According to previous data, lightning causes the highest failure percentage of 35% in high voltage application. During application, electrical performance of vegetable oil subjected to lightning voltage becomes more important for insulation design. Theoretically, lightning may strike directly to earth near overhead lines connected to transformer which in turn could cause overvoltage. To date, no one has reported any study on lightning impulse (LI) performance of RBO.

A transformer is usually composed of three-phase high-voltage windings, low-voltage windings, and probably tertiary windings. These windings can be made in the structures of disk or layer, of which each consists of many papers wrapped turn conductors. The

turn-to-turn insulation is made by multiple layer oil-impregnated papers with a thickness of ~1–2 mm. Washers are used to separate the disk conductors and thus oil ducts are formed between the disks with a thickness of ~3–10 mm. The distance between windings is relatively large, which could be tens of mm. Therefore, it is necessary to investigate the LI strengths of the RBO using larger electrode gaps which is limited in the literature.

Lightning studies can be carried out under uniform or quasi-uniform, and non-uniform electrical fields [12,14,27,28]. The insulations between turns, disks and windings of the transformer are in a quasi-uniform electric field, which is experienced by most insulation materials inside a transformer. Some other special locations of a transformer may be more challenging for insulation design. At the corner part of end winding insulation, although with the contoured angle rings, there are still tangential electric fields existing on the pressboard surface, which could facilitate the creepage discharge when it happens and creepage discharge is one of the failure reasons for large power transformers.

In addition, the bushing-lead to grounded tank could form a long distance non-uniform field. Finally, manufacturing defects e.g., protrusion on the copper conductor and contaminations resulting from long term in-service degradation e.g., particle and moisture in the oil, could cause local electric field enhancement (non-uniform field) and thus might initiate a discharge. Insulations stressed in all these non-uniform fields are the weak link of a transformer, which requires careful attentions in the processes of design and manufacture.

To sum up, the insulation system of a transformer is stressed in most quasi-uniform fields and somewhat exceptional non-uniform fields. Therefore, the lightning impulse study in this paper will be covered in both uniform or quasi-uniform fields and in non-uniform fields. To add to complexity, parameters such as testing method and gap distance used for the experiment may influence the lightning breakdown voltage performance of RBO.

2. Materials and Methods

2.1. Preparation of Sample

The samples of MO, which is an uninhibited mineral oil conforming to BS148 and two types of vegetable oils which are PO and RBO. Both PO and RBO products were obtained from cooking oil directly from the manufacturer. MO is obtained from Hyrax Oil Malaysia Sdn Bhd, which is the most popular transformer oil distributor in Malaysia. Figure 1 show the three samples used in this study.

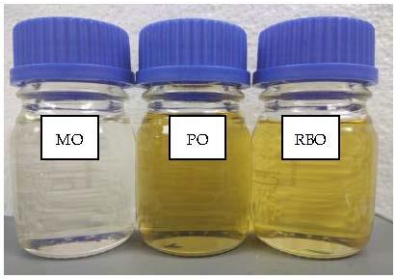


Figure 1. The samples of MO, PO and RBO.

The test samples were pre-processed through a filter using the Thermo Fisher Nalgene membrane filter with a pore size of 0.2 μm. The oil samples were then degassed after filtering and dehydrated for 48 h in the Memmert vacuum oven at 85 °C below 500 Pa (5 mbar). Impurities such as particles and moistures can be decreased by three times filtering and dehydrating the oils for two days. A further 24 h were then provided to cool the oils under vacuum to ambient temperature.

Physically, colour and appearance based on Figure 1 show that MO is a clear and bright colour oil compared to PO and RBO which that are yellow and pale yellow in colour. All the samples are transparent. The properties of MO used in this study can be obtained in Table 1. PO and RBO are normally characterised as saturated and unsaturated fatty

acids as shown in Table 2. Vitamin E, saturated and unsaturated fat per 100 g for PO and RBO are normally found in cooking oil, and they are natural exist in the oils. Based on previous studies, vitamin E does not show significant effect on the lightning breakdown voltages of the oils [12,25]. The fatty acids of PO and RBO are also in range with previous studies [22,23,27,28]. The physiochemical properties of all oil samples in this study were investigated as per specified by the standards.

Table 1. The Physicochemical properties of MO.

Parameter	Specification
Product	Hyrax hypertrans transformer oil
Appearance	Clear and bright
Standards requirement	IEC 60296: 2003
Pour point (°C)	−40
Flash point (°C)	135
Viscosity (mm^2/s) at 40 °C	10.4
Viscosity (mm^2/s) at 100 °C	3.3
Density at 15 °C ($kg/m^{3)}$	880.5
Moisture content (ppm)	7
Particle contamination (μm)	32

Table 2. Fat and vitamin E contents and physicochemical properties of PO and RBO.

Characteristic	PO	RBO
Saturated fat (g)	45.4	22.3
Mono-unsaturated fat (g)	43.0	42.3
Poly-unsaturated fat (g)	11.6	35.4
Vitamin E (mg)	4.4	1
Pour Point (°C)	−27	−33
Flash Point (°C)	283	297
Viscosity (mm^2/s) at 40 °C	45	42
Viscosity (mm^2/s) at 100 °C	12.6	10.2
Density at 15 °C (kg/m^3)	915.5	886
Mositure content (ppm)	96	84
Particle contamination (μm)	51	44

2.2. Methodology

2.2.1. Experimental Setup

The lightning impulse test configuration is as shown in Figure 2. An 8-stage impulse generator setup with 800 kV maximum voltage and 40 kJ energy to deliver the standard lightning impulse of 1.2/50 μs can be referred to in Figure 3 where (1—DC charging apparatus, 2—Impulse voltage generator, 3—Impulse voltage divider and 4—The test cell/object). The lightning breakdown voltage was measured as per the standard IEC 60897 [27] and only negative polarity lightning impulse was used in this study. Three testing methods of rising voltage, up and down and multi-level methods have been used to obtain the significance of different testing methods.

To create a uniform electric field, sphere-sphere copper electrodes were used as shown in Figure 4 and the gaps between electrodes were set to 2.0 mm, 3.8 mm, and 6.0 mm. The gap distances of 2.0 mm and 3.8 mm are the gaps that are used in the IEC standard, while for 6.0 mm gap distance, the distance is the maximum gap for the sphere electrodes can create a uniform electric field. The spherical copper electrodes of 12.7 mm in diameter (as recommended by the IEC 60897 standard) were used in this study. These electrode configurations were vertically immersed in a cylindrical test cell made from transparent acrylic with a volume of 2 l as illustrated in Figure 4.

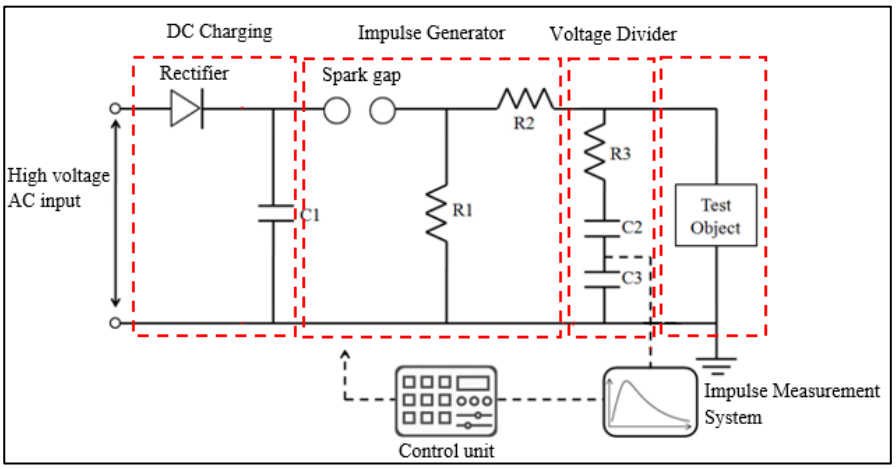


Figure 2. The test configuration for lightning impulse.

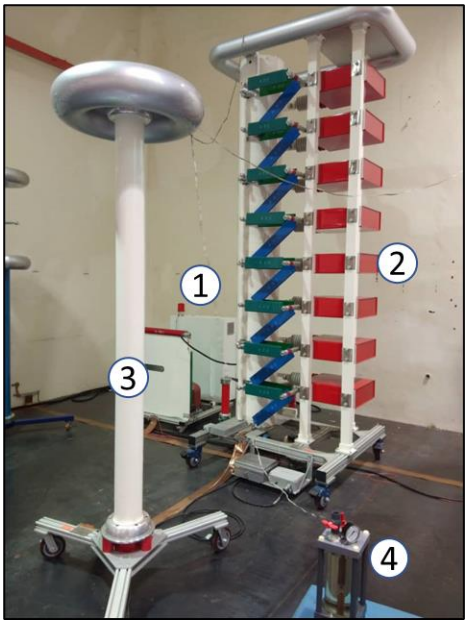


Figure 3. The lightning impulse test setup with maximum voltage of 800 kV.

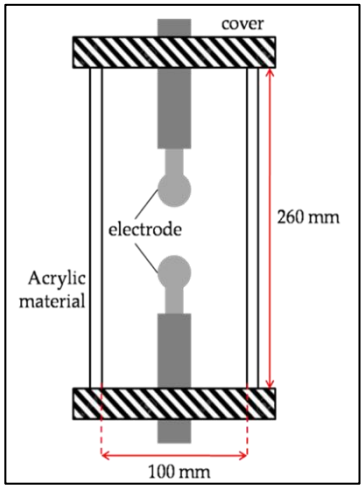


Figure 4. The electrodes configuration of uniform electric field (sphere to sphere arrangement).

To create non-uniform electric field, a vertically mounted 50 µm needle-sphere electrodes were used in Figure 5. This study aims to look at the difference in voltage breakdown for needle with two different sphere electrodes geometries. Under non uniform electric field, the testing was performed under three small gap distances (2.0 mm, 3.8 mm, and 6.0 mm), under various testing methods and five larger gap distances (10.0 mm, 20.0 mm, 30.0 mm, 40.0 mm, and 50.0 mm) using rising voltage method only.

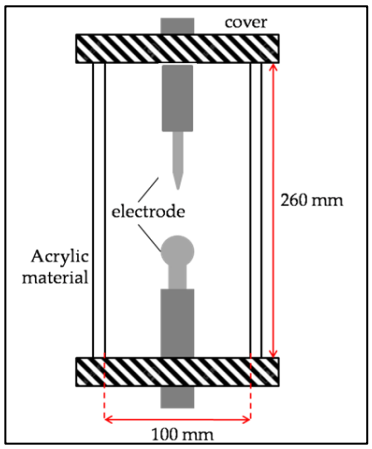


Figure 5. The electrodes configuration of non-uniform electric field (needle to sphere arrangement).

A total of 50 measurements of voltage breakdowns for each condition (uniform electric field and non-uniform electric field) were recorded for smaller gap distance. These comprised of 15 breakdown voltages of rising voltage method, 15 breakdowns voltage for up and down method and 20 breakdown voltages of multiple level method. As for the lightning impulse test in larger gap distances (10 mm to 50 mm) and only for non-uniform electric field, 10 measurements were taken for each sample as agreed in IEC60897 standard with the minimum breakdown voltage measurement are five breakdown voltages. This is due to the higher breakdown voltage resulting in larger gap distances and more carbonizing of oil and hence will affect the breakdown voltages in this study.

To comparatively study the lightning breakdown voltage of various oils, all attributions should be controlled to the same level. Otherwise, the number of weak links for various oils will be different, and thus it will be difficult to compare. To control the quality of the results, the oil samples were processed carefully as explained in Section 2. All the experiments were conducted at room temperature (27–29 °C) with 50–70% of humidity. An oil sample was replaced with a new oil for every 5 breakdown voltages.

2.2.2. Testing Methods

Various testing methods including the rising-voltage method, up-and-down method and multiple-level method have been used for oil impulse breakdown tests in both academic and industry fields over the past decades [12,27,28]. Each method has its own pros and cons, and its own validity.

1. Rising up voltage method

The method of rising voltage (1 shot/step) follows the IEC 60897 standard and can be carried out under both AC and lightning impulse breakdown tests. Due to its easy use, it is widely and successfully used in AC breakdown tests' step-up voltage control operation. Both IEC 60897 [29] and ASTM D3300 [30] adopt the rising voltage method for the isolating oil lightning impulse breakdown tests. Only shot by shot will increase the voltage, or step by step. In this method, for one set of testing, the applied voltage is increased at a specified rate (kV/s) from the specified initial voltage until a breakdown occurs. Next, the applied voltage is reduced, and the previous procedure was repeated [27]. The time interval between two consecutive shots was fixed at 60 s. A total of 15 breakdown

tests were carried out for each liquid type. The initial voltage level for this study was set at 70 kV for 2.0 mm and 150 kV for 3.8 mm and 6.0 mm with the increasing step voltage of 5 kV.

2. Up and down method

In this method, the initial voltage is set and increased until the first breakdown occurs in a fixed step voltage of range ΔU. Then, by the same step of fixed amplitude, the voltage is reduced by gradually decreasing it until breakdown does not occurs. After a certain number of breakdowns, the steps are repeated and recorded. The average value of the voltages applied is described as the voltage breakdown of 50 percent. The fixed step voltage was set to 5 kV, with an interval of 60 s between each breakdown case. A total of 30 shots was applied for each set of samples.

3. Multiple level method

A multi-level method is also known as a constant voltage method where the method is used to determine the breakdown probability. At different voltage levels, a fixed number of shots are applied, and the number of breakdowns at each voltage level is recorded. A cumulative frequency plot is carried out from the results of the breakdown voltage, and the breakdown voltage can be calculated [27]. 20 shots were applied with a loading time interval of 60 s and a step voltage of 5 kV per shot. The initial voltage level had been set at 100 kV and 150 kV for all gap distances.

3. Results and Analysis of Lightning Impulse Breakdown Voltage

3.1. Lightning Impulse Test under Uniform Electric Field

The lightning impulse breakdown voltage test of all oil samples including PO, RBO and MO as a benchmark was done for small various gap distances (2.0 mm, 3.8 mm, and 6.0 mm) and had been summarized in Figure 6. As shown in the figure, the breakdown voltage increases linearly as the electrode gap increases. This is in good agreement with the previous works [27]. The details of the breakdown voltages can be seen in Table 3.

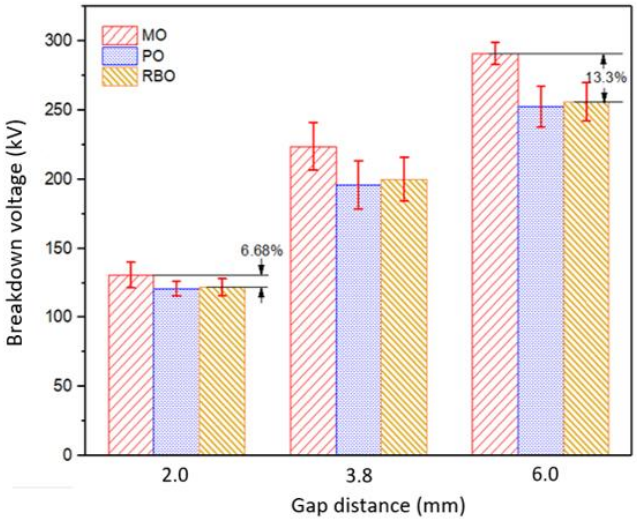


Figure 6. The 50% breakdown voltage and standard deviation of sphere to sphere configuration for small gap distances.

Table 3. The 50% breakdown voltage and standard deviation (SD) of sphere to sphere configuration at small gap distances.

Impulse Breakdown Voltage (kV) at 2.0 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
130.8	9.3	121.0	5.3	7.4	122.0	6.0	6.7
Impulse Breakdown Voltage (kV) at 3.8 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
224.0	17.2	196.1	17.5	12.5	200.2	16.0	10.6
Impulse Breakdown Voltage (kV) at 6.0 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
291.3	7.7	252.5	14.9	13.3	256.1	13.9	12.1

Using MO as the baseline, the percentage of difference (Diff oils%) between vegetable oils (RBO and PO) and MO can be calculated based on Equation (1). V_{MO} are 50% breakdown voltages of MO and the value of V_{Vo} is interchangeable 50% breakdown voltage of RBO and PO. The calculated percentage of differences are tabulated in Table 3.

Percentage of difference between MO and VO:

$$\text{Diff oil\%} = (V_{MO} - V_{VO})/V_{MO} \times 100\% \quad (1)$$

It is observed in Table 3 that the difference in voltage breakdown for PO and RBO with MO appears to be increasing with the increased gap distance. For all gap distances, the mean breakdown voltage of MO is the highest with 130.8 kV, 224.0 kV and 291.3 kV for 2 mm, 3.8 mm, and 6.0 mm gaps respectively. RBO has the second highest breakdown voltage at 122.0 kV, 200.2 kV and 256.1 kV for 2.0 mm, 3.8 mm, and 6.0 mm gaps respectively. Lastly, PO has the lowest breakdown voltage with 121.0 kV at 2.0 mm, 196.1 kV at 3.8 mm and 252.5 kV at 6.0 mm. Similar results were also obtained in [27] at 2.0 mm and 3.8 mm gap distances using a similar size of spherical electrodes for MO and PO.

At 2.0 mm gap distance, the difference of PO is 7.44%, while RBO is 6.68% lower than MO. This is the smallest percentage difference among the oils at all gap distances. For the 3.8 mm gap, the percentage difference between PO and MO is 12.5%, while RBO and MO is 10.62%. For the 6.0 mm gap, the highest percentage differences for all gap distances can be found for PO with 13.3% and 12.08% for RBO as shown in Figure 6. From this study, it was shown that the percentage difference for vegetable oils is lower by 13.5% when compared to MO for all conditions. The results show that the RBO and PO are comparable to MO in terms of uniform field lightning impulse breakdown test. Furthermore, the performance of RBO and PO is almost similar to each other.

From the results, MO is seen to have a higher breakdown voltage than PO and RBO in all situations. This is due to streamer propagation in vegetable oils being different than in mineral oil [31,32]. The previous studies in a divergent field and uniform/quasi-uniform field showed that the vegetable oils have lower impulse breakdown voltages, especially at larger gaps, than MO. This is because streamers in the vegetable oils propagate faster and further than in the MO at the same voltage level [13,15]. Liu [13] mentioned that the average time to breakdown for vegetable oil is approximated 3.8 μs compared to 5.7 μs in MO. The authors also mentioned that the streamer velocity in vegetable oil is around 10 km/s at 50 mm oil gap and reaches 30 km/s at 100 mm. The streamer velocity in MO remains at a constant speed of 1–2 km/s. Moreover, some studies suggested that these phenomena are related to the differences in the fluids chemical compositions [33,34].

From this study, the breakdown voltage differences between these PO and RBO are less than 10 kV.

Lightning impulse testing methods, including the rising voltage method, up and down method and multiple level method, are usually used for impulse breakdown tests. Each method has its own advantages and disadvantages. When comparing the lightning impulse breakdown strength of oils, the results on different methods are likely to be different. Therefore, the influence of the testing method on the lightning breakdown voltage of PO, RBO and MO was examined in this section using the standard lightning impulse. The cross comparison of impulse breakdown voltages between PO, RBO and MO are plotted in Figure 7. The 50% lightning impulse breakdown voltages of PO, RBO and MO using various testing methods are summarised in Table 4.

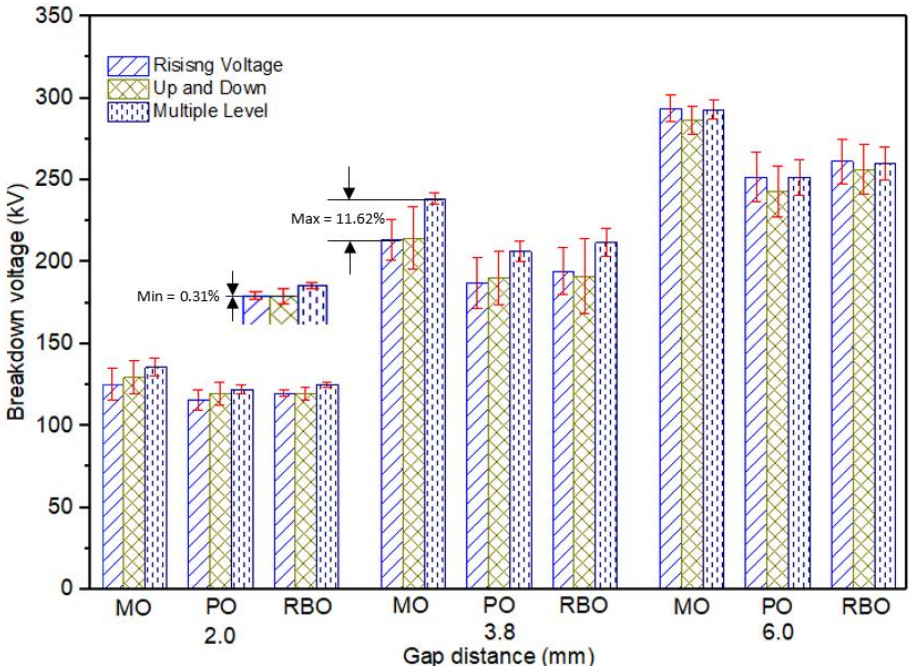


Figure 7. The comparison of 50% breakdown voltage of all samples using sphere to sphere configuration for various testing methods.

Considering the rising voltage method as the baseline as referred to in previous studies [27,28] and as the commonly used test method in the industry, the percentage of difference, Method Diff. % for the 50% breakdown voltages of oil samples between various testing methods can be calculated using Equation (2) [27]. The difference in percentage (Method Diff. %) of oil samples using the various testing methods are summarised in Table 4.

Percentage of difference of various testing method:

$$\text{Method Diff.\%} = (V_{RV}\text{-}V_{UD} @ V_{ML})/V_{RV} \quad (2)$$

where V_{RV} is Voltage rising voltage, V_{UD} is Voltage up and down and V_{ML} is voltage multiple level methods.

It can be seen in Table 4 that the multiple level method has the highest breakdown voltage among all methods for all gap distances. At 2.0 mm gap, the highest percentage difference for the multiple level method can be seen in MO with 9.48% followed by RBO with 5.14% and lastly PO with 5.10%. For the up and down method, the highest percentage difference can be seen for MO with 4.42% while RBO has the lowest percentage difference. As the gap increases to 3.8 mm, the percentage difference for the multiple level method has increased for all samples with MO having the highest difference with 11.62% followed by PO (10.19%) and RBO (8.93%). For the up and down method, the percentage difference is maintained around 2% for all oil samples. As the gap is increased to 6.0 mm, the

percentage difference for the multi-level is reduced to less than 4% with the RBO having the biggest difference with 3.73%. For the up and down method, the percentage difference is maintained low. Overall, the percentage of difference for the multiple level method for all oil samples and all gaps are less than 12%. For the up and down method, all the percentage differences are less than 5% with MO having the highest difference with 4.42%.

Table 4. The 50% breakdown voltage of sphere to sphere configuration at small gap distances.

Samples	LI Breakdown Voltage at 2.0 mm Gap Distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple Level	Method Diff%
MO	125.32	129.50	4.42	135.78	9.48
PO	115.85	119.97	2.99	122.43	5.10
RBO	119.91	119.71	0.67	125.38	5.14
Samples	LI Breakdown Voltage at 3.8 mm Gap Distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple Level	Method Diff%
MO	213.81	214.77	0.45	238.66	11.62
PO	187.26	190.26	2.21	206.35	10.19
RBO	194.58	191.40	2.22	211.95	8.93
Samples	LI Breakdown voltage at 6.0 mm gap distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple Level	Method Diff%
MO	293.83	286.54	2.48	292.93	0.31
PO	251.85	243.23	3.42	251.70	3.25
RBO	261.45	256.56	1.87	260.04	3.73

Comparing the oil samples, the various testing methods do not affect the ranking of oil samples in which vegetable oils are always showing lower LI breakdown voltage than MO [27]. It can be seen from Figure 5 that RBO has comparable 50% breakdown voltages with PO at various gap distances and testing methods where the highest percentage of difference is less than 11.0%. On the other hand, PO and RBO have lower breakdown voltages compared to MO with the highest percentage of difference being less than 10.19% for all methods and gap distances, which agreed with the previous finding [27]. The lightning impulse test in this study used sphere electrodes 12.7 mm in diameter according to ASTM D3300. Katim N.I.A had conducted the lightning impulse breakdown voltage test for 2.0 mm and 3.8 mm gap distances using similar electrodes size with oil volume of 300 mL [27]. In this study, the volume of the oil is 2000 mL and is much larger than the study by [27]. Hence, a comparison between the previous work and this work is made in this section. The 50% lightning breakdown voltage from [27] and this work can be obtained in Table 5. The 50% lightning breakdown voltage difference between this study and the previous study by Katim N.I.A shows that both breakdown voltages are comparable to each other [27]. The percentage of differences observed are less than 7% for MO and less than 7.5% for PO. The different oil volumes in both experiments did not significantly affect the breakdown voltage of oil samples. This might be due to smaller gap distances which give very minimal effect for the breakdown voltage of the oils [27,35–37]. Overall, the 50% lightning breakdown voltages from this study are comparable with the previous study.

Table 5. The comparison of 50% breakdown voltage with the previous study of sphere to sphere configuration [27].

Samples	Lightning Impulse Breakdown Voltage (kV)	
	Gap Distances (mm)	
	2.0	**3.8**
MO in this study	130.76	224.03
MO of previous study	140.3	236.33
Diff%	6.8	5.2
PO in this study	121.03	196.14
PO of previous study	130.67	206
Diff%	7.4	4.8

3.2. Lightning Impulse Test under Non-Uniform Electric Field

Due to manufacturing defects such as exposed conductors and contaminations resulting from in-service degradation of insulation (particles and moisture), contaminations in the oil will possibly cause strong non-uniform fields to exist in transformers. These strong non-uniform fields could lead to the enhancement of local electric fields and initiate a discharge in transformer oils. In addition, streamer initiation and breakdown voltage for an insulating liquid in a strong non-uniform field, i.e., point-sphere electrodes, are proved to be closely associated with liquid composition. Therefore, it is aimed to study the electrical performance of RBO and PO based oil in a strong non-uniform field in terms of the breakdown strength.

3.2.1. Effect of Small Gap Distances

The lightning breakdown voltages of the dielectric insulation oil under a non-uniform field were found to be dependent upon the composition of oil samples and configuration of electrodes [38–42]. The 50% breakdown voltages of PO, RBO and MO under the non-uniform field at 2.0 mm, 3.8 mm and 6.0 mm gaps can be referred to in Figure 8. A total of 50 breakdown voltage measurements were made which comprised of 15 breakdown voltages from the rising voltage method, 15 breakdown voltages from the up and down method and 20 breakdown voltages from the multiple level method.

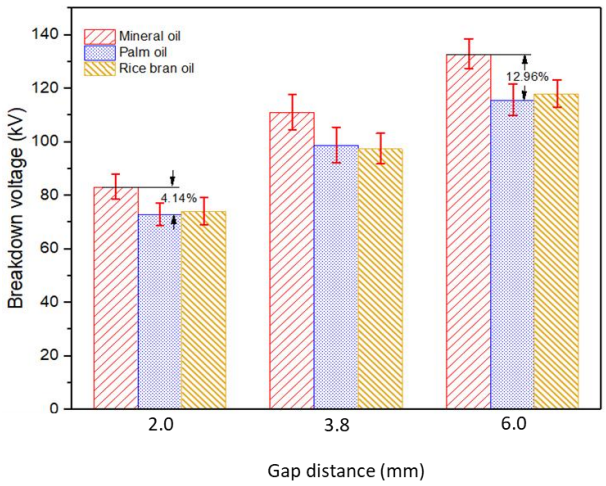


Figure 8. The 50% breakdown voltage and standard deviation (SD) of needle to sphere configuration for small distances.

According to Figure 8, generally, the 50% breakdown voltage for all samples increases as the gap distance increases. The results show that there is a significant effect of breakdown

voltage with various gap distances which agreed with the previous finding [12,41,42]. MO has the highest 50% breakdown voltage at all gap distances. The highest percentage difference of 50% breakdown voltage MO and vegetable oils (RBO and PO) is less than 16% for all conditions as shown in Table 6.

Table 6. The 50% breakdown voltage and standard deviation (SD) of needle to sphere configuration at 2.0 mm, 3.8 mm and 6.0 mm.

Impulse Breakdown Voltage (kV) at 2.0 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
83.31	4.57	73.02	4.14	7.22	74.19	5.21	5.73
Impulse Breakdown Voltage (kV) at 3.8 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
111.19	6.60	98.87	6.6	11.08	97.53	5.66	12.29
Impulse Breakdown Voltage (kV) at 6.0 mm Gap Distance							
MO		PO		Diff Oil%	RBO		Diff Oil%
Mean	SD	Mean	SD		Mean	SD	
133.00	5.49	115.81	5.84	12.92	118.1	5.09	11.18

From the Table 6, at gap distance of 2.0 mm, the 50% breakdown voltages of MO and PO are 83.31 kV and 73.02 kV respectively. They are higher from the previous results of [28] by only 60 kV. The difference of percentage of PO toward MO at 2.0 mm, 3.8 mm and 6.0 mm gap distances are 7.22%, 11.08% and 12.92% respectively. Meanwhile, the difference between RBO and MO are 5.73%, 12.29% and 11.18% for 2.0 mm, 3.8 mm, and 6.0 mm, respectively. PO has the highest 50% breakdown voltage difference among vegetable oils when compared to MO which is around 5 kV to 14 kV. Even though RBO almost has a larger breakdown voltage than PO, the 50% breakdown voltage of RBO is quite close with PO at all gap distances. These findings are due to the physical and chemical properties of the RBO, and PO are almost similar according to [13,14,23].

A similar study was carried out on the various testing methods for a non-uniform field lightning impulse test. The influence of testing method on the lightning breakdown voltage of MO, PO and RBO was examined using the standard negative lightning impulse. The cross comparison of 50% lightning impulse breakdown voltages of RBO, PO and MO are plotted in Figure 9. Meanwhile, the percentage difference of the 50% breakdown voltage under various testing methods is summarized in Table 7.

From Table 7, there is only a small effect of testing methods that can be seen on the breakdown voltages of all samples at all gap distances. The highest percentage difference is less than 7.50%. This finding is close to the previous work by Yvone [12] which is 13.8%. Similar to the lightning breakdown voltage under a uniform field, the multi-level method has the highest 50% breakdown voltages compared with other methods. For all testing methods, MO has the highest 50% breakdown voltages followed by RBO and PO. This result agreed with the previous section where the streamer propagation is the main reason which cause MO to have higher breakdown voltages than vegetable oils. Besides that, the particle contamination of oil samples might be also influenced the breakdown voltage. The floating particles tend to bridge the oil gap and ultimately lead to a breakdown. This increasing of particle contaminations possibly due to the promotion of streamer initiation and results in the reduction of time to breakdown. Based on Tables 1 and 2, the amount of particle content inside the PO and RBO a little bit higher than MO, which might the reason why PO and MO having lower breakdown voltage compared to MO.

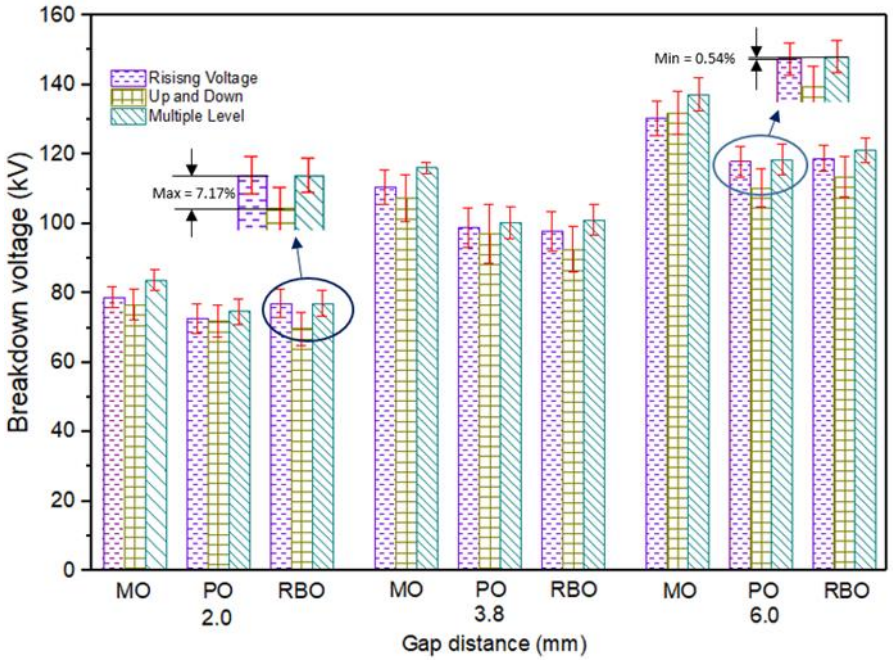


Figure 9. The comparison of 50% breakdown voltage of all samples using needle to sphere configuration for various testing methods.

Table 7. The 50% breakdown voltage of needle to sphere configuration for various testing method at 2.0 mm, 3.8 mm and 6.0 mm.

Samples	Breakdown Voltage at 2.0 mm Gap Distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple Level	Method Diff%
MO	78.75	76.15	4.20	82.06	3.30
PO	72.61	71.88	3.79	74.71	2.81
RBO	75.01	69.63	7.17	77.01	2.67
Samples	Breakdown Voltage at 3.8 mm Gap Distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple Level	Method Diff%
MO	110.48	107.32	7.50	116.02	4.78
PO	98.84	97.14	1.72	100.18	1.36
RBO	97.72	92.54	5.30	101.13	3.49
Samples	Breakdown Voltage at 6.0 mm Gap Distance (kV)				
	Testing Methods				
	Rising Voltage	Up and down	Method Diff%	Multiple level	Method Diff%
MO	130.30	131.89	5.28	137.18	1.22
PO	117.79	110.34	6.32	118.43	0.54
RBO	118.83	113.51	4.48	121.08	1.89

Based on the analysis in Table 7, the performances of the lightning breakdown voltage for PO and RBO are comparable with MO. The lowest percentage of difference for all samples is just 0.54% and the highest percentage of difference is 7.5%, corresponding to only 1 kV and 3 kV. Among all different testing methods, the multiple level method always has the highest 50% breakdown voltage for all samples at various gap distances, followed

by the rising voltage method and the up and down method. Therefore, breakdown voltage does not affect the ranking of liquids for the aim of comparison purposes even when using different testing methods [12,39,43].

3.2.2. Effect of Larger Gap Distances

The dielectric failure of oil is initiated by some weak links. As the volume of electrically stressed oil increases, the probability that weakness is present in the oil volume also rises. Therefore, for a large oil gap, it is necessary to investigate whether the reduction in the dielectric strength of alternative transformer oils is comparable to that of mineral oil or not. The large gap represents the situation between the lead of the winding and the wall of the transformer tank, which is earthed [43].

In this section, the study is carried out to investigate the influence of gap distances on the lighting breakdown voltage under a non-uniform field. The lightning impulse breakdown voltage test was performed using the rising-up method. This study uses a needle to sphere electrode following the IEC Standard 60897 [12,35,39,44,45]. All tests were carried out at 2.0 mm, 3.8 mm, 6.0 mm, 10.0 mm, 20.0 mm, 30.0 mm, 40.0 mm and 50.0 mm gap distances.

The 50% breakdown voltage with different gap distances is plotted in Figure 10. The comparison of 50% impulse breakdown voltages of all samples is shown in Table 8. From the graph, the 50% breakdown voltages for all samples increase as the gap distances increase. A similar pattern was also found in [13,39]. The 50% breakdown voltages of the PO and RBO are much lower than the MO at all gap distances under a non-uniform field. The difference in the 50% breakdown voltages became larger as the gap distance increases where the highest percentage of difference can be up to 30%. At a gap distance of 25.0 mm, the percentage of differences for the 50% breakdown voltages between MO and PO is in the range of 17.1% and 20.3% while for RBO, it is between 15.4% and 20.3%.

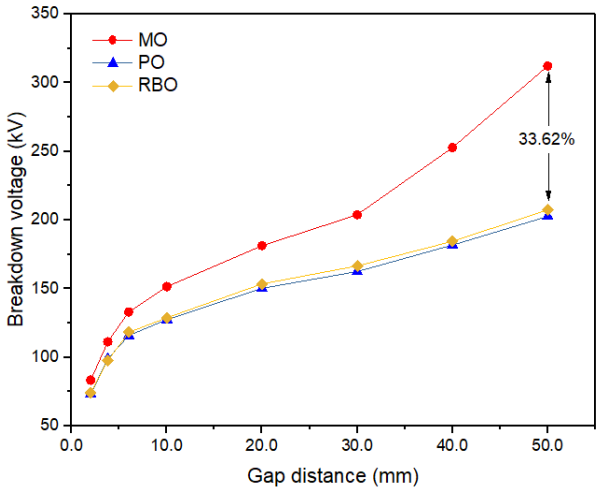


Figure 10. The 50% breakdown voltage of needle to sphere configuration for various gap distances.

Based on Figure 10 and Table 8, the 50% breakdown voltages of PO and RBO are lower than the MO for all gaps observed, and the differences become larger as the gap distances increased. The breakdown voltages of PO and RBO are almost identical for all gaps. The lowest percentage difference of RBO and PO towards MO are 14.9% and 15.82% where the value is almost 23 kV and 24 kV each. This pattern is also in line with previous researchers [13,46] where the LI breakdown voltage of mineral oil becomes higher than vegetable oils. The percentage of difference between RBO and MO at 50 mm gap is around 33.62% whereas for PO and MO it is around 35.11%. The difference was more pronounced at larger gap distances [12,38].

Table 8. The 50% breakdown voltage of needle to sphere con figuration under larger gap distances.

Oil Samples		50% Breakdown Voltage (kV) at Various Gap Distances (mm)				
		10.0	**20.0**	**30.0**	**40.0**	**50.0**
MO	Mean	151.41	181.22	203.78	252.77	312.22
	SD	2.07	2.19	10.09	1.90	3.58
PO	Mean	127.46	150.19	162.39	181.73	202.60
	SD	1.96	5.90	1.48	3.60	4.57
Diff%		15.82	17.12	20.31	28.10	35.11
RBO	Mean	128.81	153.41	166.47	184.45	207.31
	SD	0.89	0.90	2.44	1.58	3.89
Diff%		14.9	15.35	20.31	27.04	33.62

This finding agreed with the studies by [15,36]. The reason why this phenomenon occurred is due to the different types of streamers happening in the process of breakdown. According to [36], small gaps breakdown is caused by slow streamers of which the average propagation velocity is low. With increasing gap distances, the fast streamer appears at the breakdown voltage level and starts to take over the control of breakdown. There is a range of transition gap distance where slow and fast streamer-induced breakdowns can occur. Once this transition occurs at certain gaps, the fast streamers will purely control the breakdown of the oil. In the case of natural esters, the appearance of this transition gap distance happens earlier than MO, which causes lower breakdown voltages at very large gaps.

Besides that, according to [47–49] the chemical compositions and electron affinity of dielectric insulation fluids play a dominant role in the streamer propagation characteristics. The chemical structure of RBO and PO is based on a glycerol backbone that consists of three fatty acids groups. This group consists of saturated and unsaturated fatty acids. Normally, PO contains approximately 50% saturated fatty acids, with 44% palmitic acid (C16:0), 5% stearic acid (C18:0), and trace amounts of myristic acid (C14:0). The unsaturated fatty acids are approximately 40% oleic acid (C18:1) and 10% polyunsaturated linoleic acid (C18:2) and linolenic acid (C18:3). Meanwhile, RBO contains palmitic acid (22.5%) as the major saturated fatty acid. It is high in oleic acid (monosaturated fat) with 41.2%. Linoleic acid in the largest component (33%) of polyunsaturated fatty acids, followed by low level (1.25%) linolenic acid. PO and RBO have some percentage of C=C double bonds in the oleic and linoleic acid side chains. The presence of these bonds can cause a low ionisation potential which leads to higher streamer propagation speeds and hence lowers the lightning impulse breakdown voltages of RBO, and PO compared to MO. Besides that, there is a high amount of electronegative oxygen atoms existing in the RBO and PO molecular structure. Therefore, it is expected to be the reason for the low performance of lightning impulse breakdown in RBO and PO. At the same voltage, the streamer in vegetable oils propagates further with higher velocity and more branches than MO. According to a study done by [15], the streamer velocity for PO is around 3.5 km/s whereas for MO it is only 2.0 km/s which can be a reason for vegetable oils having lower breakdown voltages than MO.

4. Statistical Analysis of Experimental Data

Statistical methods have been extensively used in dielectric failure studies. The failure probability depends on the electrical stress applied in the liquid. Normally, the Weibull distribution approach is generally accepted in the field of electrical insulation as the one that best fit the data approximating the failure and dielectric strength [50–53]. Usually, the mean breakdown voltage (50% breakdown voltage) and standard deviation are used to represent the breakdown voltage distribution, based on the assumption that the oil breakdown voltage follows the normal distribution. The estimation of breakdown voltages

at 1% and 50% probabilities of failure of all oil samples can be determined using statistical analysis. The estimation of 1% probability is identified as the lowest breakdown voltage that can be expected from the test sample or sometimes referred to as the withstand voltage. Meanwhile, the 50% probability is the mean breakdown voltage of the test sample. These values are important for a transformer designer to design the appropriate insulation of the transformer.

The withstand voltage is critically important in designing power transformer insulation. Weibull distribution is usually used to fit the breakdown voltages and the withstand voltage can be deduced based on the fitted curve. Weibull statistic method is based on a stability postulate [52,53]. The weak-link theory gives the breakdown probability. Weibull analysis is an effective method of determining reliability characteristics and trends of a population using a relatively small sample size of field or laboratory test data. The lightning withstand voltages for all samples were obtained by using Weibull distribution for which the cumulative distribution function is given in Equation (3).

$$F(x) = 1 - e^{-(x/\alpha)^{\beta}}, x \geq 0 \quad (3)$$

where, α and β are scale and shape parameters while x is the measured breakdown data.

For each sample, all the breakdown voltage were compiled and group together. Next, the cumulative probabilities were determined based on the number of breakdown events at each voltage level. The Weibull cumulative distribution function given in Equation (3) was used to fit the data and the shape and scale parameters were obtained. The breakdown voltages at 1% and 50% probabilities could be determined based on these parameters [53].

4.1. Weibull Probability for MO, PO and RBO under Uniform Electric Field

The Weibull distributions for each oil sample were plotted based on the data obtained in this study and can be referred to Table 9. Table 9 shows the breakdown voltages at 1% and 50% probabilities of failure for Weibull distribution at 2.0 mm, 3.8 mm, and 6.0 mm gap distances.

Table 9. The 1% and 50% probabilities of failure for MO, PO and RBO at small gap distances under uniform electric field.

Breakdown Probability	Impulse Breakdown Voltage (kV) at 2.0 mm Gap Distance		
	MO	PO	RBO
1%	100.19	100.60	108.13
50%	131.76	122.50	120.4
Shape, α	1.48	1.09	0.49
Scale, β	130.37	121.46	119.91
Breakdown Probability	Impulse Breakdown Voltage (kV) at 3.8 mm Gap Distance		
	MO	PO	RBO
1%	177.81	153.97	138.55
50%	226.65	202.54	198.22
Shape, α	2.44	2.26	2.48
Scale, β	224.04	200.23	196.14
Breakdown Probability	Impulse Breakdown Voltage (kV) at 6.0 mm Gap Distance		
	MO	PO	RBO
1%	260.99	209.96	196.71
50%	292.13	258.00	254.21
Shape, α	1.09	1.98	2.12
Scale, β	291.28	256.08	252.54

At 1% probability for the withstand voltage of 2.0 mm gap distance, RBO has a higher withstand voltage (with 108.13 kV) than PO (100.19 kV) and MO (100.60 kV). The percentage difference in breakdown voltages between RBO and MO is 7.9% and for RBO

and PO, it is 0.11%. However, for probabilities of failure at 10% and above, MO has the highest withstand voltage compared to PO and RBO. The percentage difference of 50% probability MO between PO and RBO is 7.03% and 8.62% respectively.

Meanwhile, MO has the highest 1% probability of breakdown voltage at 3.8 mm and 6.0 mm gap distances with 177.81 kV and 260.99 kV respectively compared to all oil samples. PO is the second best after MO for both gaps with 202.54 kV and 258 kV respectively followed by RBO with 198.22 kV (3.8 mm) and 254.1 kV (6.0 mm). The percentage of difference for PO and RBO with MO at 1% and 50% are in a range between 10.64% and 22.08%. As indicated in Table 9, the 50% breakdown voltages of PO and RBO are lower than MO, which is consistent with the previously drawn conclusion using various testing methods. Moving down to smaller breakdown probability, the difference between PO and RBO with MO becomes smaller.

4.2. Weibull Probability for MO, PO and RBO under Non-Uniform Electric Field

The 1% and 50% probability failure of breakdown voltages for MO, PO and RBO using Weibull distribution under non uniform electric field at all gap distances is tabulated in Table 10.

Based on Table 10, the difference in probabilities of breakdown voltage between MO and vegetable oils is very low at smaller gap distances. At 2.0 mm gap distance, the difference between MO and vegetable oils ranges from 4.4 kV to 5.8 kV (5.73% to 7.2%). However, the voltage breakdown probability differed for MO and vegetable oils at 3.8 mm gap distance, with an average difference of 15 kV (12.3%). However, the distribution of vegetable oils is well fitted with the reference line at all gap distances. At 6.0 mm gap distance, the distributions of all samples were well plotted at the probability line. The 1% and 50% probability were predicted lower but almost close to the probability line. The difference of percentage at 50% probability of MO, PO and RBO between the breakdown voltage distributions and the probability line are calculated to be in the range of 1.4%, 1.6% and 1.1% respectively.

Meanwhile the 1% and 50% probability failure of breakdown voltages for MO, PO and RBO at larger gap distances indicate that the differences in the breakdown voltages at 50% and 1% probabilities between MO and PO/RBO are significantly higher at all various gap distances. The probabilities of breakdown voltages between PO/RBO and MO increase as the gap distance increases where the highest percentage of difference can be up to 36%. The percentage difference between RBO and MO on the 1% probability is in the range from 11% to 32%, while for PO is in the range of 14% to 33%. The 50% probable breakdown voltages also show the average increasing percentage difference between MO and PO/RBO when the gap distance increases. The percentage of difference of MO and PO is in the range of 15% to 35%, while RBO is in the range of 14% to 33%. On the other hand, the highest percentage difference between PO and RBO at 1% and 50% probabilities are comparable with a value less than 5%.

4.3. Determination of Empirical Equation for Non-Uniform Electric Field Study

The breakdown voltage of vegetable oils at very large gaps is important for their application in large power transformers. In this part, the relationship between the results under the lightning impulse and the previously published data under step voltage will be built up so that the breakdown voltages of vegetable oils at very large gaps can be estimated. Based on the previous studies by [13,27,28,45,54] a power law model was found to be suitable to represent the relationship between various parameters in dielectric insulation transformer liquids especially for lightning impulse. The relationship between the lightning breakdown voltage and the gap distance using the power law model is based on Equation (4) where V is the lightning breakdown voltage, d is the gap distance while a and b are constant value.

$$V = a \times d^{b} \quad (4)$$

Table 10. The 1% and 50% probabilities of failure for MO, PO and RBO at small gap distances under non-uniform electric field.

Breakdown Probability	Impulse Breakdown Voltage (kV) at 2.0 mm Gap Distance		
	MO	PO	RBO
1%	63.44	59.89	57.71
50%	79.31	73.60	74.87
Shape, α	8.97	10.5	6.27
Scale, β	80.85	74.93	76.57
Breakdown Probability	Impulse Breakdown Voltage (kV) at 3.8 mm Gap Distance		
	MO	PO	RBO
1%	94.39	79.08	80.74
50%	112.27	99.77	98.31
Shape, α	12.38	18.20	17.52
Scale, β	113.98	101.82	100.00
Breakdown Probability	Impulse Breakdown Voltage (kV) at 6.0 mm Gap Distance		
	MO	PO	RBO
1%	113.73	96.90	103.68
50%	133.75	116.57	118.96
Shape, α	16.03	22.93	21.00
Scale, β	135.63	118.45	120.32
Breakdown Probability	Impulse Breakdown Voltage (kV) at 10.0 mm Gap Distance		
	MO	PO	RBO
1%	142.30	121. 11	125.75
50%	151.62	127.84	128.96
Shape, α	18.07	13.14	19.64
Scale, β	151.41	127.46	128.82
Breakdown Probability	Impulse Breakdown Voltage (kV) at 20.0 mm Gap Distance		
	MO	PO	RBO
1%	175.22	132.31	149.95
50%	181.60	150.96	153.46
Shape, α	20.10	21.03	18.02
Scale, β	181.23	150.19	153.42
Breakdown Probability	Impulse Breakdown Voltage (kV) at 30.0 mm Gap Distance		
	MO	PO	RBO
1%	189.45	157.12	158.61
50%	204.93	162.70	166.97
Shape, α	12.46	17.06	13.11
Scale, β	203.78	162.39	166.48
Breakdown Probability	Impulse Breakdown Voltage (kV) at 40.0 mm Gap Distance		
	MO	PO	RBO
1%	246.72	172.29	180.58
50%	253.66	182.41	184.68
Shape, α	6.15	7.84	9.42
Scale, β	234.71	181.74	184.45
Breakdown Probability	Impulse Breakdown Voltage (kV) at 50.0 mm Gap Distance		
	MO	PO	RBO
1%	287.75	192.97	195.13
50%	313.47	203.36	207.01
Shape, α	5.29	8.82	7.48
Scale, β	315.78	202.60	207.32

A similar approach was adopted in this thesis to determine the empirical formulas for the relationship between breakdown voltage (kV) and gap distance, d (mm) of withstand voltages (1% probability) and breakdown voltages at 50% probability for all samples. The 1% withstanding voltage and 50% breakdown voltage fittings of these equations can be obtained in Figures 11 and 12. Most of these data fit well toward the power law Equation, where the r^2 values are from 0.83 to 0.97. From the equations, it is observed that the constant values of α and β for both vegetable oils at 1% and 50% probabilities are comparable to MO.

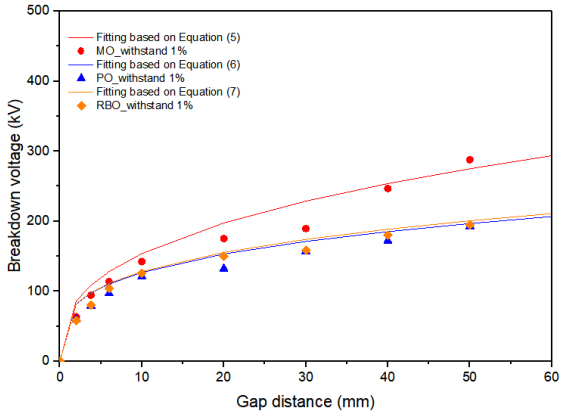


Figure 11. Lightning impulse breakdown voltage fitting at empirical equation at 1% withstand voltage.

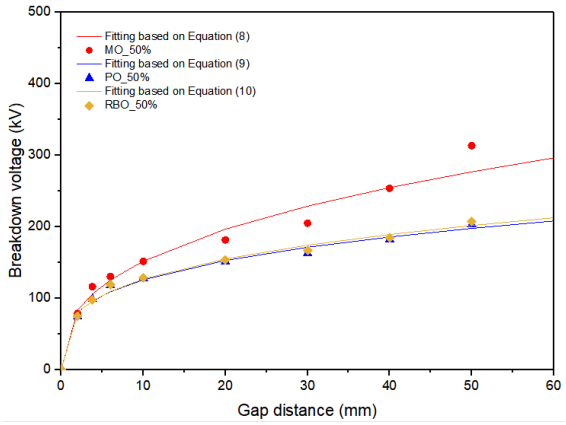


Figure 12. Lightning impulse breakdown voltage fitting at empirical equation at 50% breakdown voltage.

For lightning breakdown voltage under non-uniform field:

$$V_{MO}_withstand\ (1\%) = 74.62 \times d^{\,0.597} \quad (5)$$

$$V_{PO}_withstand\ (1\%) = 70.532 \times d^{\,0.4763} \quad (6)$$

$$V_{RBO}_withstand\ (1\%) = 70.808 \times d^{\,0.4844} \quad (7)$$

$$V_{MO}_breakdown\ (50\%) = 67.123 \times d^{\,0.3605} \quad (8)$$

$$V_{PO}_breakdown\ (50\%) = 67.639 \times d^{\,0.0.273} \quad (9)$$

$$V_{RBO}_breakdown\ (50\%) = 87.754 \times d^{\,0.2775} \quad (10)$$

The lightning breakdown voltage under a non-uniform field shows that most of the equation matches the data quite well as shown in Figures 11 and 12. The 1% withstanding voltage and 50% breakdown voltage matches the line based on Equations (5)–(7). It is found that the 50% breakdown voltage in this study show a higher breakdown than previous

studies but become closer to each other as the gap distance increases. Overall, the equation for the non-uniform field in this study can be used to predict the failure on a designed transformer.

5. Conclusions

The lightning impulse (LI) breakdown voltage under a uniform electric field, RBO and PO have comparable performances to MO, which is promising results for liquid insulation. In addition, there are notable effects of testing methods on the lightning breakdown voltage of all samples including the rising-voltage method, up and down method and multiple level method. The LI breakdown voltage of PO is almost similar to RBO at various gap distances and testing methods. The values of MO in all testing methods are higher than PO and RBO at all gap distances.

For the lightning impulse breakdown voltage under a non-uniform electric field, results show that LI of PO and RBO are slightly lower than MO for all conditions. However, the difference is so small and comparable to each other. The testing methods include the rising-up voltage, up and down and multiple level methods. For all of these, no significant effect on the lightning breakdown voltage was observed. The values of MO for all methods are higher than PO and RBO at all gap distances.

Furthermore, the lightning breakdown voltage under a non-uniform field extended at larger gap distances. Due to the small effect on the lightning breakdown voltage of the testing method at small gap distances, the rising voltage method is recommended. This is the common testing method used is standard IEC 60897 and ASTM 3300. The study found the effects on lightning breakdown voltage increased as gap distances increased. Overall, the findings are reliable and consistent with the previous research on larger gap distances under a non-uniform field. Based on the testing data under a non-uniform LI, an empirical formula had been proposed. The proposed equation fits well with the data from the literature.

Author Contributions: The research study was carried out successfully with contribution from all authors. The main research idea, experiment works, and manuscript preparation were contributed by M.T.I. and M.H.A.H. contributed to the manuscript preparation and research idea. N.S.S. and N.I.A.K. assisted on finalizing the research work and manuscript. N.F.M. and R.A.R. gave several suggestions from the industrial perspectives. M.T.I. and J.A. provided the data analysis and helped proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

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