Pertanika J. Sci. & Technol. 25 (S): 69 - 78 (2017)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Lightning Breakdown Voltages of Refined Bleached and Deodorised Palm Oil under Needle-plane Configuration

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ABSTRACT

In recent years, vegetable oil such as Palm Oil (PO) has been identified as a potential alternative dielectric insulating fluid for transformers. It is biodegradable, non-toxic and has high flash and fire points. In this paper, a study on the positive lightning impulse breakdown voltages of PO under non-uniform field is carried out. The testing was carried out using needle-plane electrodes configuration at gap distances of 25 mm and 50 mm. Rising voltage, 1 and 3 shots per step testing methods were used and 3 types of Refined Bleach and Deodorized Palm Oil (RBDPO) and Mineral Oil (MO) were examined. It was found there is no significant effect on the breakdown voltages of all samples. The breakdown voltages of all RBDPO at 50% probability are comparable with MO. At 1% probability and gap distance of 50 mm, the breakdown voltages of all RBDPO are lower than MO.

Keywords: Lightning breakdown voltage, non-uniform field, palm oil, transformers

INTRODUCTION

Oil filled transformers form the majority type of transformers in high voltage power system networks (Nynas Ab, 2004). The conventional dielectric insulating fluid used in transformers is Mineral Oil (MO) (Nynas Ab, 2004). However, MO is not -biodegradable, non-renewable, and has low flash points. Due to the increasing concern for the environment vegetable oils have been proposed as dielectric insulating fluid in transformers. Extensive studies had been carried out previously on different types of vegetable oils and used in small and medium transformers (Cigre, 2010; Hopkinson et al., 2006; Rycroft et al., 2014).

ARTICLE INFO

Article history:
Received: 24 August 2016
Accepted: 03 Jun 2017

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ISSN: 0128-7680

Palm Oil (PO) is one of vegetable oil considered for transformers application. It is easily available in Indonesia and Malaysia (Agriculture, 2015) where it is used in food preparation and lubricants, biodiesel and biofuel (Mekhilefa et al., 2011; Reddy et al., 2014). Generally, PO is classified under the natural ester family and consists of glycerol and fatty acids which are known as triglycerides (Cigre, 2010). It contains an almost balanced mixture of saturated and unsaturated fatty acids (Cigre, 2010).

Studies too had been done to examine the lightning breakdown characteristics of PO under non-uniform field (Thien et al., 2014; Thien et al., 2015; Thien et al., 2016b; Vukovic et al., 2011). The point-plane or point-sphere configurations create non-uniform field which can be used to simulate the imperfections that could occur in transformers. Therefore, the lightning breakdown voltages of dielectric insulating fluids under non-uniform field are important as the parameter for transformers design (Thien et al., 2016a). It was found that based on needle-sphere electrodes configuration, the lightning breakdown voltages of PO were comparable to MO under positive polarity (Thien et al., 2014; Thien et al., 2015; Thien et al., 2016b). This paper investigates the lightning impulse breakdown voltages of 3 types of Refined Bleached and Deodorized Palm Oil (RBDPO) based on needle-plane electrodes configuration. The first section of the paper examines the effect of the rising voltage, 1 and 3 shots per step testing methods on the positive lightning breakdown voltages of the RBDPO. Next, the breakdown voltages of RBDPO at 1% and 50% probability obtained based on rising voltage, 1 shot per step method are computed by Weibull and normal distributions and compared with MO.

EXPERIMENTAL DESCRIPTION

Investigated samples

Three samples of RBDPO and 1 sample of MO were examined. The compositions of saturated/unsaturated fats and vitamins of the RBDPO are given in Table 1. RBDPOB has the highest quantity vitamin E followed by RBDPOA and RBDPOC while only RBDPOC has vitamin A.

Table 1
Fat, vitamin E/A contents of RBDPO

Contents	Samples		
	RBDPOA	RBDPOB	RBDPOC
Saturated fat (g)	44.4	43.0	45.4
Poly-unsaturated fat (g)	12.2	14.0	11.6
Mono-unsaturated fat (g)	43.3	43.0	43.0
Vitamin E (mg)	50.0	75.0	4.4
Vitamin A (μg)	-	-	264

Test setups

The lightning breakdown voltage tests of all samples were carried out using needle-plane electrodes as shown in Figure 1. The tip radius curvature of the needle electrode was 50±5 μm while the diameter of the plane electrode was 200 mm with an edge radius of 3 mm. The oils were filled in a cubic transparent Perspex test cell with an internal volume of 10 litres. All tests were carried out at gap distances of 25 mm and 50 mm. Standard positive lightning impulse of 1.2/50 μs was delivered by the impulse generator with maximum voltage of 420 kV.

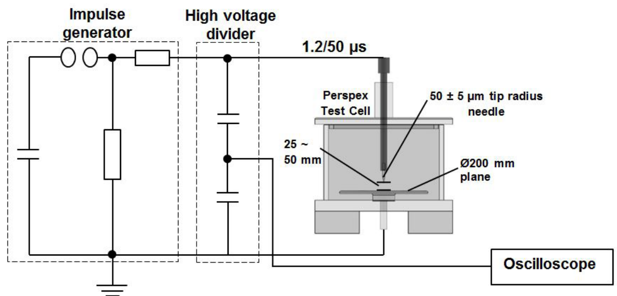


Figure 1. Test configuration for the lightning impulse

Testing methods

All measurements were carried out based on rising voltage method. The initial voltages were set at 70 kV and 140 kV respectively for both gap distances of 25 mm and 50 mm. The voltage increment was set to 10 kV.

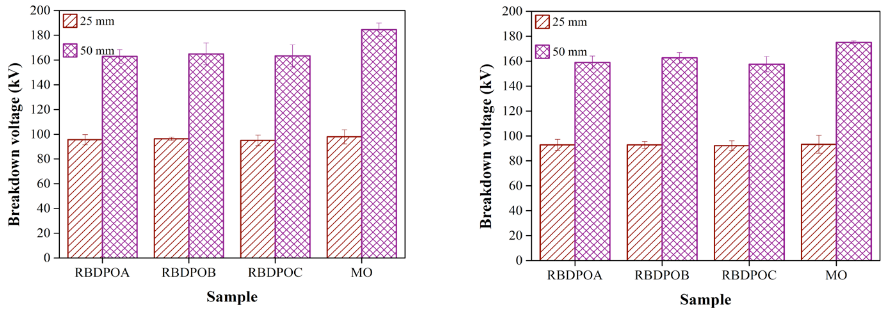
The first test consisted of 5 breakdown voltages data for each sample based on the 1 shot per step method according to IEC 60897 and 3 shots per step method according to ASTM 3300 (IEC 60897, 1987; ASTM 3300, 2012). The testing was repeated after standing time intervals of 3 to 5 minutes. This set of data was obtained in order to compare the differences between both methods stated in IEC 60897 and ASTM 3300. The second test consisted of 15 breakdown voltages data for each sample at 1 shot per step method and the analysis on the breakdown voltages at 1% and 50% probabilities was carried out based on Weibull and normal distributions.

RESULT AND ANALYSIS OF DATA

Rising voltage – 1 shot per step and 3 shots per step

The 50% lightning breakdown voltages for all RBDPO and MO based on 1 shot per step are shown in Figure 2(a). At gap distance of 25mm, MO shows the highest breakdown voltage followed by RBDPOB, RBDPOA and RBDPOC with values of 98.0 kV, 96.4 kV, 95.7 kV and 95.1 kV. The same pattern is observed at gap distance of 50 mm where MO has the highest breakdown voltages with a value of 184.6 kV. For RBDPO, the highest breakdown voltage is RBDPOB followed by RBDPOC and RBDPOA with values of 165.0 kV, 163.4 kV and 162.9 kV respectively.

Figure 2(b) shows the 50% lightning breakdown voltages for all RBDPO and MO based on 3 shots per step method. The same pattern is observed as in rising voltage 1 shot per step method where the highest breakdown voltage is MO with values of 93.3 kV and 175.1 kV at gap distances of 25 mm and 50 mm respectively. At gap distance of 25 mm, the breakdown voltages of RBDPOA and RBDPOB are comparable to MO with a value of 92.9 kV. The breakdown voltage of RBDPOC is slightly lower than RBDPOA and RBDPOB with a value of 92.2 kV. While at gap distance of 50 mm, RBDPOB has the highest breakdown voltage followed by RBDPOA and RBDPOC with values of 162.7 kV, 159.0 kV and 157.6 kV respectively.

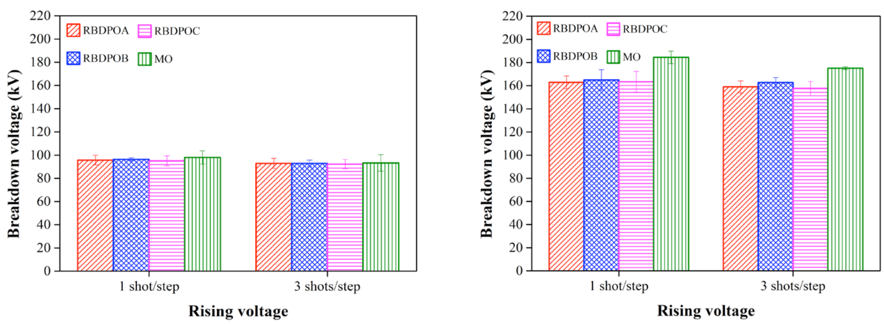


(a) (b)

Figure 2. 50% breakdown voltages of all samples based on rising voltage (a) 1 shot per step; (b) 3 shots per step

Analysis results

It was found that the 50% lightning breakdown voltages of all samples obtained by 1 shot per step method are slightly higher than 3 shots per step method as shown in Figure 3(a) and 3(b). The highest percentages of differences are between 1% and 5% at both gap distances of 25 mm and 50 mm. Since both 1shot per step and 3 shots per step methods show similar results, rising voltage 1shot per step method are recommended after considered their technical operations and times consumed for results obtained.



(a) (b)

Figure 3. Comparison between 50% breakdown voltages obtained based on 1 and 3 shots per step methods of all samples at gap distances of (a) 25 mm; (b) 50 mm

Table 2 shows the breakdown voltages for all samples and the percentage of difference between the RBDPO samples and MO. Taking MO as a benchmark, it was found that the breakdown voltages of all RBDPO are comparable to MO where the highest percentage of difference is less than 3% at gap distance of 25 mm under both 1 and 3 shots per step methods. At gap distance of 50 mm, the differences between all RBDPO and MO are slightly high where the highest percentages of differences are around 11.7% and 10% for both 1 and 3 shots per step methods respectively. Among all the RBDPO, RBDPOB has the closest breakdown voltage with MO with percentage of difference less than 10% at both gap distances. Thus, based on the results obtained, the possibility to replace MO with RBDPO is high.

Table 3 shows the average velocities of all samples that were determined based on the gap distance over the time to breakdown recorded for each breakdown event. The average velocities of all RBDPO are slightly slower than MO at gap distance of 25 mm but faster than MO at gap distance of 50 mm. At gap distance of 25 mm, the average velocities for all RBDPO are the same while at gap distance of 50 mm, the average velocity of the RBDPOA is the highest followed by RBDPOB and RBDPOC.

Table 2
Breakdown voltages using rising voltage 1 shot/step and 3 shots/step testing method at gap distances of 25 mm and 50 mm

Sample	Breakdown voltages at gap distance 25 mm (kV)			
	1 shot/step	% difference between RBDPO and MO	3 shots /step	% difference between RBDPO and MO
RBDPOA	95.7	2.3	92.9	0.5
RBDPOB	96.4	1.7	92.9	0.4
RBDPOC	95.1	3.0	92.2	1.2
MO	98.0	-	93.3	-
Sample	Breakdown voltages at gap distance 50 mm (kV)			
	1 shot/step	% difference between RBDPO and MO	3 shots /step	% difference between RBDPO and MO
RBDPOA	162.9	11.7	159.0	9.2
RBDPOB	165.0	10.6	162.7	7.1
RBDPOC	163.4	11.4	157.6	10.0
MO	184.6	-	175.1	-

Table 3
Average velocity of all samples

Sample	Velocity (km/s) at gap distance 25 mm		Velocity (km/s) at gap distance 50 mm	
	1 shot/step	3 shots/step	1 shot /step	3 shots /step
RBDPOA	1.5	1.5	4.2	4.3
RBDPOB	1.5	1.5	2.8	2.7
RBDPOC	1.5	1.6	2.8	2.3
MO	1.8	1.9	2.0	2.0

Lightning withstand voltages

Weibull distribution is commonly used to fit all the breakdown data of electrical insulation. The cumulative distribution function for Weibull distribution is given by Equation 1 (Liu, 2011).

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

Where α and β are scale and shape parameters, while x represents the measured breakdown data.

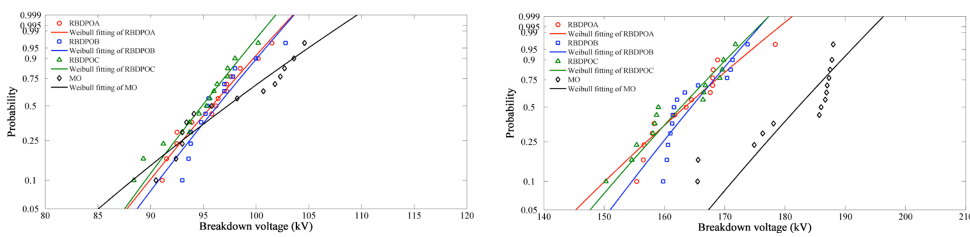
Based on its shape and scale parameters, the withstand voltage can be calculated. Other common distribution that is used to analyse the breakdown data of electrical insulation is normal distribution. The probability function is given by Equation 2.

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^{2}\right) \quad (2)$$

Where μ and σ are mean and standard deviation parameters, while x is the measured breakdown data.

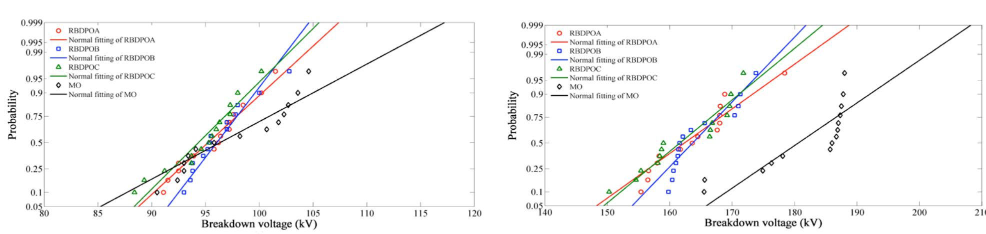
According to the normal distribution, the withstand voltage can be determined based on mean and standard deviation. The Weibull and normal fittings for all samples can be seen in Figure 4(a), 4(b), 5(a) and 5(b). At gap distance of 25 mm, both Weibull and normal distributions can represent the all samples quite well. There is however, a slight deviation of both Weibull and normal fittings at gap distance of 50 mm.

The breakdown voltages at 1% and 50% probabilities for both Weibull and normal distributions are shown in Table 4. At gap distance of 25 mm, MO has a slightly lower



(a) (b)

Figure 4. Weibull probability fittings of all samples at gap distances of (a) 25 mm; (b) 50 mm



(a) (b)

Figure 5. Normal probability fittings of all samples at gap distances of (a) 25 mm; (b) 50 mm

Table 4
Breakdown voltages of all samples at 1% and 50% breakdown probabilities

Sample	Breakdown probability	Breakdown voltage at gap distances (kV)			
		25 mm	50 mm	25 mm	50 mm
		W.D	N.D	W.D	N.D
RBDPOA	1%	83.1	86.1	135.0	142.5
	50%	95.8	95.2	163.4	162.3
RBDPOB	1%	84.3	89.6	143.2	150.0
	50%	96.3	96.0	164.4	163.6
RBDPOC	1%	83.2	85.9	139.0	144.4
	50%	94.9	94.3	162.7	161.6
MO	1%	78.2	80.6	158.6	159.8
	50%	97.3	96.3	182.1	180.6

* W.D – Weibull distribution and N.D – Normal distribution

breakdown voltage at 1% probability than all RBDPO where the highest percentages of differences are 7.8% and 6.8% for both Weibull and normal distributions. At gap distance of 50 mm, MO has the highest breakdown voltage at 1% probability voltage where the highest percentages of differences with all RBDPO are 15% and 10.8% for both Weibull and normal distributions. The breakdown voltages of all RBDPO at 50% probability are slightly lower than MO where the highest percentages of differences are 10.6% and 10.5% at both gap distances. The difference of the breakdown voltages among all RBDPO at 1% and 50% probabilities are quite small where the percentage of differences are between 0.2% and 5% at both gap distances. It is observed that at 1% probability, the breakdown voltages of all samples based on normal distribution are higher than Weibull distribution. However, at 50% probability, the breakdown voltages based on normal distribution are lower than Weibull distribution. Both normal and Weibull distribution show similar breakdown voltages results, Weibull distribution is recommended since it was commonly used in most of the previous studies.

CONCLUSION

Under the current needle-plane configuration, the positive lightning breakdown voltages of all RBDPO are slightly lower than MO at both gap distances of 25 mm and 50 mm. The range of the percentages of differences between all RBDPO and MO is between 1% and 11.7%. The composition of the saturated/unsaturated fats and vitamins of the RBDPO show no significant effect on the lightning breakdown voltages where the highest percentages of difference among all RBDPO samples are less than 2.3%. There is also no significant effect between 1 and 3 shots per step methods on the breakdown voltages of all samples where the range of the percentages of differences is between 1% and 5%. Considering the technical operation and time consumed for results obtained, rising voltage 1 shot/step is commonly used. It is also observed that the average velocities of all samples increase as the gap distance increases. Based on the Weibull and normal distributions analyses, it was found that the percentages of differences for the breakdown voltages at 1% probability between all RBDPO and MO can be up to 15%.

ACKNOWLEDGEMENT

The authors would like to thank Ministry of Education and Universiti Putra Malaysia for the funding under FRGS scheme (03-02-13-1280FR), (03-02-13-1279FR), Putra IPM and IPB schemes (GP-IPM/2013/9401500), (GP-IPB/2014/9440801). Special thanks to Hyrax Oil Sdn. Bhd and Malaysia Transformer Manufacturing Sdn. Bhd. for technical support.

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