

# Breakdown Strength of Transformer Oil Filled with Carbon Nanotubes under Various Gap Distances.

N. S. Suhaimi, M. T. Ishak, M. F. Din, M. M. Ariffin, S. Razali, N. A. Amin

Faculty of Engineering, National Defence University of Malaysia, Sg. Besi Camp, 57000 Kuala Lumpur, Malaysia.  
E-mail: sabrina15.eec@gmail.com, mtaufiq@upnm.edu.my, faizdin@hotmail.com, maslinamohdariffin@gmail.com, sakinahrazali88@gmail.com, amin.aqilah@yahoo.com

**Abstract**— A new class of colloidal insulating transformer oil is formulated by dispersing CNT nanomaterials with mineral oil in purpose to enhance the breakdown strength performance of existing transformer oil. This paper represents the experimental studied dealing with the influence of CNT nanomaterials mix with transformer mineral oil in term of AC breakdown voltage at various gap distances. The concentrations of CNT nanomaterials were measured in range 0.01g/L to 0.2g/L. The impact of three gap distances (1.5mm, 2.5mm and 3.5mm) for mushroom-mushroom electrode configuration is studied in order to observe and compare the trend between conventional mineral oil and CNT nanofluids. To employ CNTs as effective reinforcement in mineral oil, proper dispersion methods need to be applied. Based on the investigations, it revealed that the breakdown voltages for CNT nanofluids gain better performance compare to reference mineral oil. However, as concentrations increased, the breakdown voltages tend to decreased. Looking into 1% probability of breakdown failure which were modelled by using Weibull distribution, it was figure out that CNT nanofluids have huge potential to enhance the performances of breakdown strength for transformer application.

**Keywords**— transformer; mineral oil; CNT; breakdown voltage; Weibull.

## I. INTRODUCTION

The life expectancy and satisfactory operation of transformers are mainly depending on the transformer insulating oil. The mineral oil serves mainly with two purposes which are as insulation in transformer and another one as a coolant agent to remove heat from the windings. Recently, lots of studies have been done with purpose at enhancing the dielectric properties of insulating oil. The studies have been conducted to prove the efficiency of nanofluid by dispersing nanomaterials with based oil samples. There were various types of nanomaterials that have been investigated such as TiO<sub>2</sub>, CeO, Al<sub>2</sub>O<sub>3</sub> and others [1]–[4]. However, there are very constrained data regarding CNT nanomaterials.

A carbon nanotube (CNT) is a mysteriously fascinating material for a component of nano-suspension because of their unique structure and remarkable mechanical, thermal, and electrical [5]–[7]. CNT renowned for conducted heat and cold very well which mean it has high thermal conductivity. This paper represents the studies on the breakdown voltage of transformer oil filled with the various concentrations of CNT nanomaterials at various gap distances considering the effect of dispersant and the potential mechanisms. This experimental setup was done according to IEC 60156 standards [8].

## II. EXPERIMENTAL WORK

### A. Preparation of CNT Nanofluids

The based mineral oil has been supplied by Hyrax Oil Sdn. Bhd. while CNT properties were described in Table I.

TABLE I  
THE PROPERTIES OF CARBON NANOTUBES

Parameter	Value
Outer Diameter	< 8nm
Inner Diameter	2 – 5nm
Length	10 - 30µm
Purity	95%

The CNTs were weighed in five different concentrations (0.01g/L, 0.03g/L, 0.05g/L, 0.1g/L and 0.2g/L) by using an analytical balance. After weighed, the CNT nanomaterials were mixed with mineral oil. The CNT nanomaterials were dispersed through ultra-sonication equipment for one hour. In order to disperse CNT nanomaterials, the sound energy with frequency less than 25 kHz was applied towards the CNT nanofluids/ mixture. The sonication technique was implemented utilizing a sonicator equipment with 700W power rating and the amplitude was set at 10% and the dispersion timing cycle was set to 5 seconds on; 3 seconds off intervals for duration of 60 minutes.

### B. AC Breakdown Voltage Test

AC breakdown test was performed by using BAUR Automatic 50 Hz Electrical Breakdown Voltage Tester with proper procedures and precautions according to IEC 60156 standard. The rate of rise voltage was set at 2kV/s and initial standing time of 2 minutes was fixed before voltage applied. The BAUR breakdown voltage analyser consists of a test cell with 400 ml capacity of oil samples with mushroom-mushroom shaped electrodes. The gap distance between the electrodes is possible to vary based on design and specification requirement. As for this experiment, breakdown voltages of CNT nanofluids with three different gap distances were evaluated. The CNT nanofluids samples were carefully filled into the test cell in order to avoid the air bubbles formation. There were total of 50 measurements of breakdown voltage were measured for each samples.

### III. STATISTICAL ANALYSIS

For manufacturing a transformer, a designer requires to refer the minimum withstand voltage level of the insulating oil rather than based on average breakdown voltage produce. Generally, there are two popular types of statistical analysis used to interpret the probability distribution of breakdown failure which are normal distribution and Weibull distribution [9]. Weibull distribution is more preferable due to ability to provide reasonable accurate failure analysis and failure forecasts by referring to extremely small amount of samples [10]. Therefore, Weibull distribution was used in this paper to calculate the probability of breakdown failure at certain level. There are three significant probability of distribution in breakdown voltages which have been identified in this paper, which are 1%, 50% and 90%. As for insulating material for high voltage equipment, probability failure of 1% is known as risk level while 50% of probability is the standard value in order to design transformer insulation. The high expected breakdown voltage for industry usually measured at 90% probability of breakdown voltage which analysed based on Weibull distribution.

#### A. Analysis Data (1.5mm Gap Distance)

The AC breakdown voltages patterns of CNT nanofluids at 1.5mm gap distance for 50 readings were plotted in Fig. 1. Based on the graphs, there were no upward or downward trend exist, instead there are fluctuation observed in all range of CNT nanofluids. These prove the effectiveness of energy control of AC Breakdown Analyser.

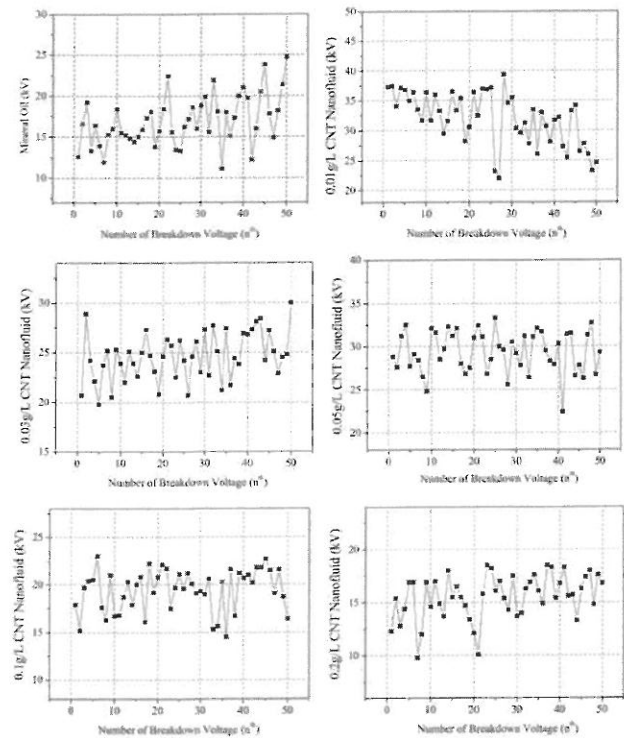


Fig 1 The AC breakdown voltages pattern for various CNTs concentration dispersed in mineral oil at 1.5mm gap distance.

The comparison of mean AC breakdown voltages and standard deviations of CNT nanofluids and mineral oil were shown in Table II and Fig. 2. The standard deviation values measured in all types of oil samples were quite small and considerable. Moreover, most of CNT nanofluids breakdown voltage values deviates lower than reference sample which is mineral oil. The data was considered valid due to the measurement of 50 readings of breakdown voltages were concentrated around the mean value.

TABLE II  
COMPARISON OF AC BREAKDOWN VOLTAGES FOR 1.5MM GAP DISTANCE

Oil Samples	Mean (kV)	Standard Deviation
Mineral Oil	16.93	3.06
0.01g/L CNT Nanofluid	31.99	4.41
0.03g/L CNT Nanofluid	24.60	2.40
0.05g/L CNT Nanofluid	29.33	2.40
0.1g/L CNT Nanofluid	19.46	2.18
0.2g/L CNT Nanofluid	15.57	2.09

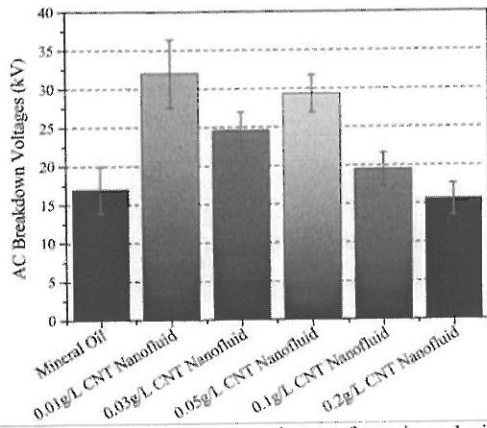


Fig 2 Mean AC breakdown voltages for mineral oil and CNT nanofluids at 1.5 mm gap distance.

It was figure out that all types of CNT nanofluids performances were higher than mineral oil except for 0.2g/L of CNT's concentration. For 0.01g/L of CNT nanofluid, there was an improvement as much as 88.95% compared to mineral oil, while 0.03g/L improved 45.30%, 0.05g/L improved 73.24% and 0.1g/L improved 14.94% at 1.5 mm gap distance. However, as the amount of CNTs increased to 0.2g/L concentration, the average value of AC breakdown voltage was slightly decreased to 15.57kV or resembled as -8.02% decrement compared to mineral oil sample. Fig. 3–Fig. 8 show the Weibull distribution analysis to model the AC breakdown voltage for mineral oil and 0.01g/L - 0.2g/L concentration of CNT nanofluids at 1.5mm gap distance.

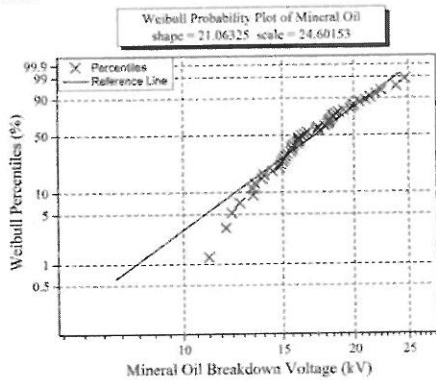


Fig 3 Weibull distributions of mineral oil at 1.5mm gap distance.

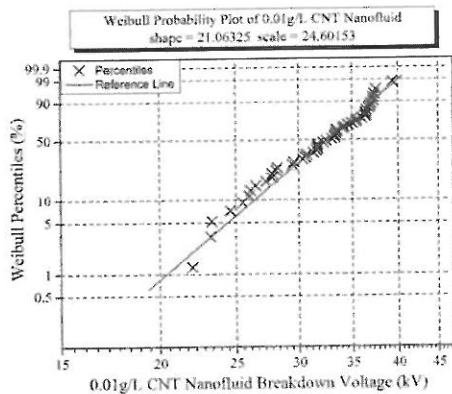


Fig 4 Weibull distributions of 0.01g/L CNT Nanofluid at 1.5mm gap distance.

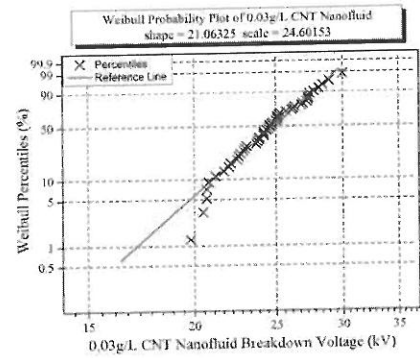


Fig 5 Weibull distributions of 0.03g/L CNT Nanofluid at 1.5mm gap distance.

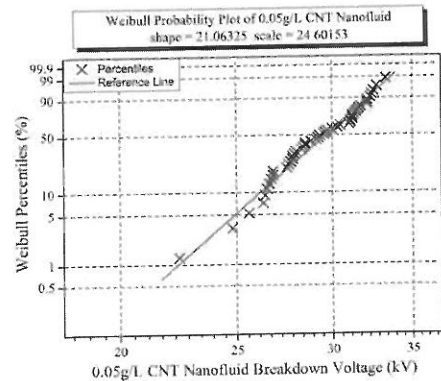


Fig 6 Weibull distributions of 0.05g/L CNT Nanofluid at 1.5mm gap distance.

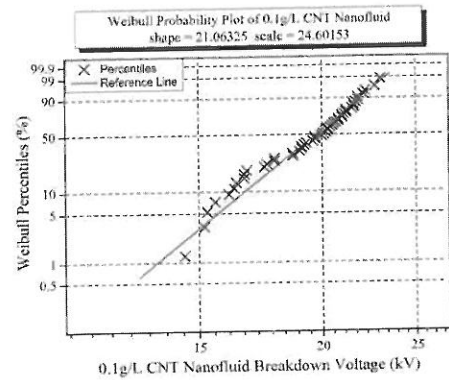


Fig 7 Weibull distributions of 0.1g/L CNT Nanofluid at 1.5mm gap distance.

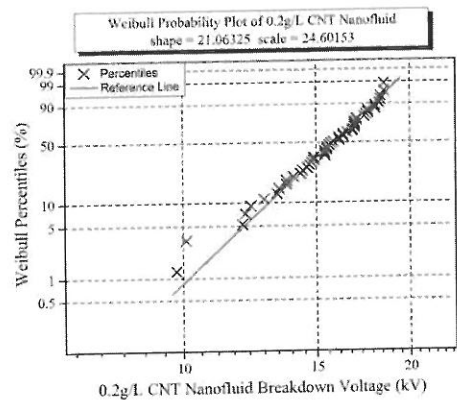


Fig 8 Weibull distributions of 0.2g/L CNT Nanofluid at 1.5mm gap distance.

Table III shows the probability of breakdown failure at 1%, 50% and 90%. At 1% breakdown probability, CNT nanofluid achieved an increase of 1.71 times compare to mineral oil. As for 50% normal breakdown failure probability which fit for designing transformer gain 1.90 times increment while for 90% probability of breakdown voltage achieved 1.76 increments. For early stage of investigation at 1.5mm gap distance, it can be seen that CNT nanomaterials could possibly influenced the breakdown voltage performance of based mineral oil. For further investigation and verification, the same methods have been applied but with two different gap distances.

TABLE III  
PROBABILITY OF AC BREAKDOWN VOLTAGES (1.5MM GAP DISTANCE)

Oil Samples	P1 (%)	P50 (%)	P90 (%)
Mineral Oil	8.24	17.11	21.04
0.01g/L CNT Nanofluid	20.40	32.50	37.10
0.03g/L CNT Nanofluid	17.06	24.86	27.66
0.05g/L CNT Nanofluid	22.35	29.66	32.14
0.1g/L CNT Nanofluid	13.60	19.74	21.94
0.2g/L CNT Nanofluid	10.17	15.81	17.93

### B. Analysis Data (2.5mm Gap Distance)

The scattered diagram of AC breakdown voltage for 50 readings of breakdown voltages of mineral oil and CNT nanofluids at 2.5 mm gap distance were tabulated in Fig. 9. Referring to the graphs, the distributions of data seem fluctuated for all types of oils samples. Thus, all the data is considered as acceptable and valid to be analysed further.

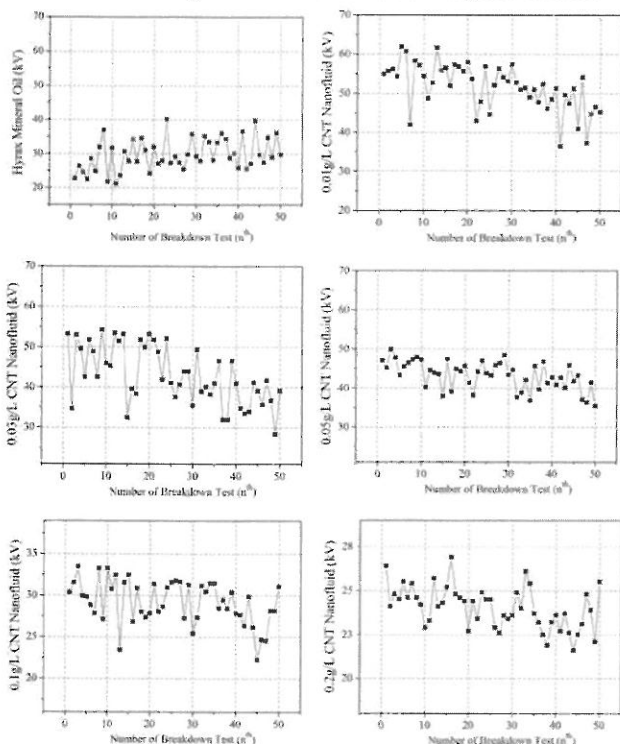


Fig 9 The AC breakdown voltages pattern for various CNTs concentration dispersed in mineral oil at 2.5mm gap distance.

TABLE IV  
COMPARISON OF AC BREAKDOWN VOLTAGES FOR 2.5MM GAP DISTANCE

Oil Samples	Mean (kV)	Standard Deviation
Mineral Oil	29.75	4.64
0.01g/L CNT Nanofluid	51.68	5.85
0.03g/L CNT Nanofluid	43.07	7.10
0.05g/L CNT Nanofluid	38.46	5.43
0.1g/L CNT Nanofluid	29.25	2.60
0.2g/L CNT Nanofluid	24.04	1.19

The standard deviations produced were small and it can be considered that the data were very close to the average value. A high standard deviation means that the data was spread out and unacceptable.

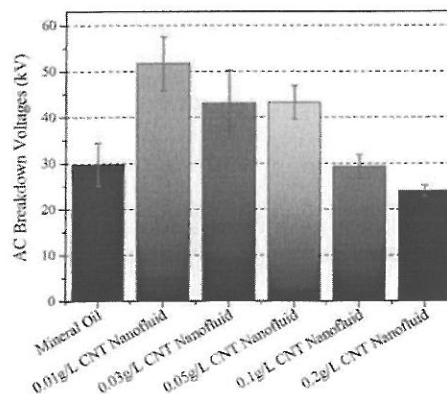


Fig 10 Mean AC breakdown voltages for mineral oil and CNT nanofluids at 2.5mm gap distance.

Fig. 10 shows the comparison of mean AC breakdown voltages between mineral oil and five concentrations of CNT nanofluids. It can be observed that 0.01g/L CNT nanofluid having the highest mean breakdown voltage which is 51.68kV (73.70% improvement) compared to other oil samples. Results for 0.03g/L and 0.05g/L CNT nanofluids performances also achieved good results compared to the reference mineral oil breakdown voltage. These proved CNT nanofluids could possibly improve reliability of transformer oil in future. However, different results were achieved for 0.1g/L and 0.2g/L CNT nanofluids. There were -1.68% and -19.22% decrements of breakdown performances compared to reference mineral oil. This occurrence might be due to the agglomeration of CNTs in the based mineral oil which causes performance to drop.

Thus, in order to investigate more detailed, observation of pattern and behaviour of 50 readings of mineral oil and CNT nanofluids electrical breakdown at 2.5 mm gap distance has been model by using Weibull distribution analysis as shown in Fig. 11 – Fig. 16.

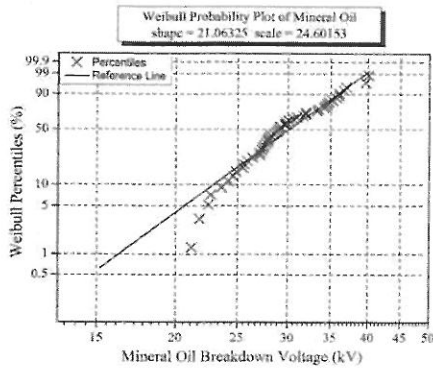


Fig 11 Weibull distributions of mineral oil at 2.5mm gap distance.

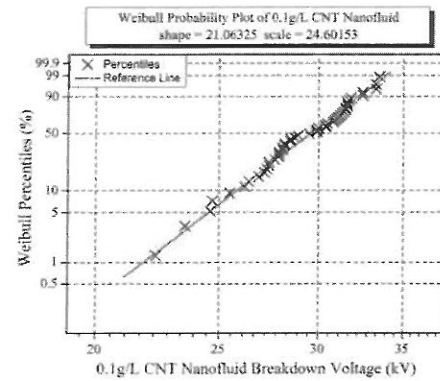


Fig 15 Weibull distributions of 0.1g/L CNT Nanofluid at 2.5mm gap distance.

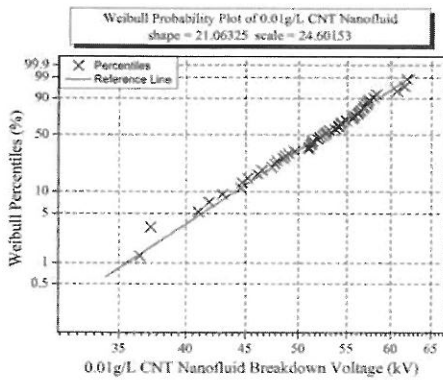


Fig 12 Weibull distributions of 0.01g/L CNT Nanofluid at 2.5mm gap distance.

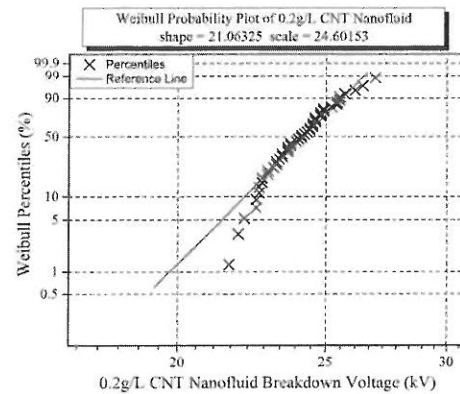


Fig 16 Weibull distributions of 0.2g/L CNT Nanofluid at 2.5mm gap distance.

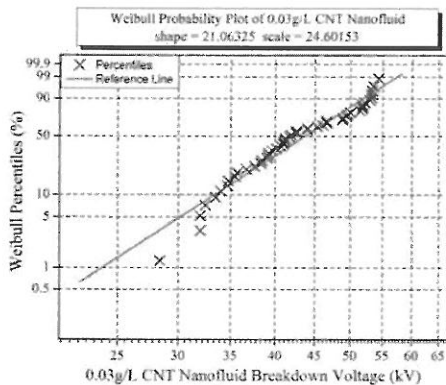


Fig 13 Weibull distributions of 0.03g/L CNT Nanofluid at 2.5mm gap distance.

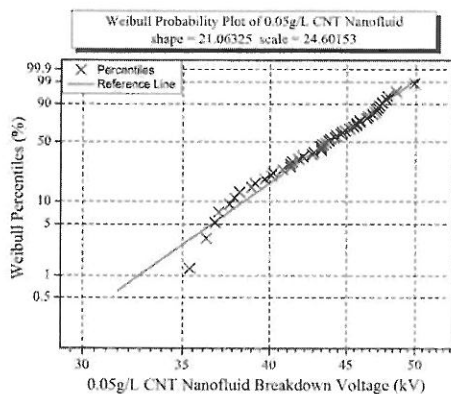


Fig 14 Weibull distributions of 0.05g/L CNT Nanofluid at 2.5mm gap distance.

TABLE V  
PROBABILITY OF AC BREAKDOWN VOLTAGES (2.5MM GAP DISTANCE)

Oil Samples	P1 (%)	P50 (%)	P90 (%)
Mineral Oil	16.29	30.09	35.85
0.01g/L CNT Nanofluid	35.58	52.38	58.44
0.03g/L CNT Nanofluid	23.88	43.73	51.90
0.05g/L CNT Nanofluid	23.62	39.03	45.00
0.1g/L CNT Nanofluid	21.80	29.60	32.27
0.2g/L CNT Nanofluid	19.78	24.18	25.60

The probability of 1% withstands voltages provide significant value in designing transformer. Based on Fig. 12 and Table V, 0.01g/L CNT nanofluid provides good linearity in Weibull plots and produce the highest breakdown voltage value among the oil samples. There was 118.42% increment achieved compared to typical transformer mineral oil used in this experiment. Instead, in 50% probability and 90% probability of breakdown voltage, there were 1.74 and 1.63 times increments were achieved. Thus it can be seen that CNT nanomaterials were constantly getting higher results compared to mineral oil. Previously, at 1.5mm gap distance, 0.1g/L and 0.2g/L CNT nanofluids probability of breakdown failure having slightly decreased compare to mineral oil. However, at 2.5 mm gap distance, all types of CNT nanofluids unexpectedly achieved probability of breakdown voltages more than the standard mineral oil.

### C. Analysis Data (3.5mm Gap Distance)

The tabulation of 50 readings of AC breakdown voltages was plotted in scatter graph as shown in Fig. 17. The breakdown voltages data plotted were level-off with the increasing test number, thus the measurements were considered valid and acceptable for mineral oil, 0.01g/L, 0.03g/L, 0.05g/L, 0.1g/L and 0.2g/L CNT nanofluids.

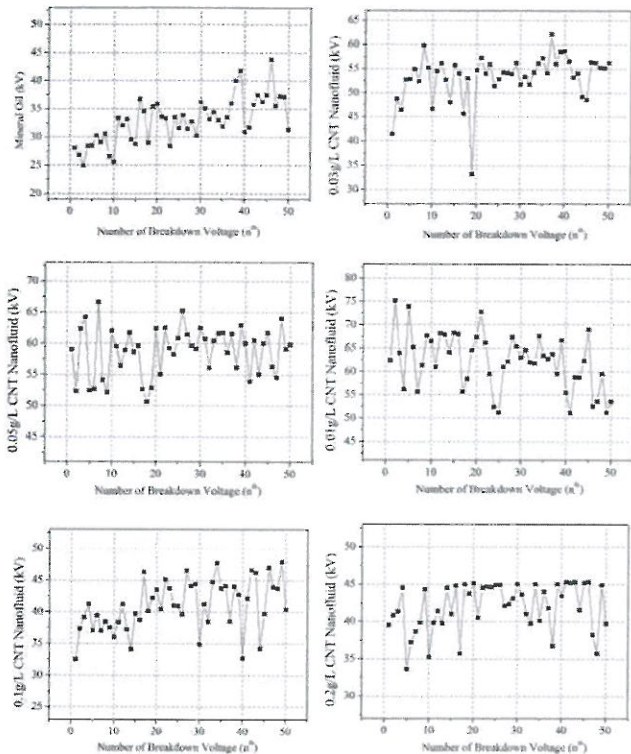


Fig 17 The AC breakdown voltages pattern for various CNTs concentration dispersed in mineral oil at 1.5mm gap distance.

Table VI compute the average and standard deviation achieved from breakdown voltages measurements for mineral oil and five different concentrations of CNT nanofluids. While Fig. 18 plot the data according to Table VI.

TABLE VI  
PROBABILITY OF AC BREAKDOWN VOLTAGES (3.5MM GAP DISTANCE)

Oil Samples	Mean (kV)	Standard Deviation
Mineral Oil	32.94	3.40
0.01g/L CNT Nanofluid	57.00	9.40
0.03g/L CNT Nanofluid	53.25	4.74
0.05g/L CNT Nanofluid	41.75	3.22
0.1g/L CNT Nanofluid	40.93	3.97
0.2g/L CNT Nanofluid	41.98	3.19

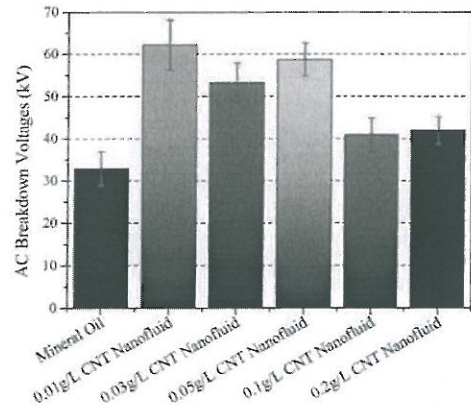


Fig 18 Mean AC breakdown voltages for mineral oil and CNT nanofluids at 3.5mm gap distance.

The average breakdown voltages for CNT nanofluids were higher than standard mineral oil with 24.06 differences. The highest improvement was achieved by 0.01g/L CNT nanofluid with 73.02% increment while the lowest improvement was achieved by 0.1g/L CNT nanofluids with 24.27% increment. Hence, it can be considered that CNT nanomaterials were possible to enhance the breakdown voltage for transformer oil application more than standard industry transformer oil. The weibull analysis results of 50 breakdown failures for mineral oil and various concentrations of CNT nanofluids are shown in Fig. 19 - Fig. 24.

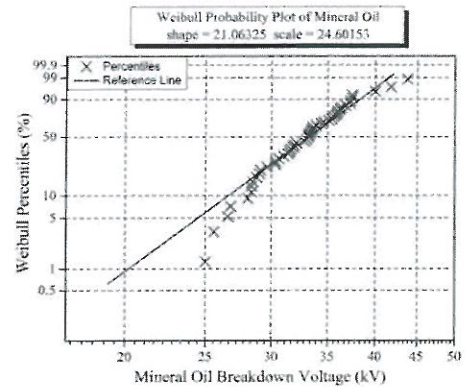


Fig 19 Weibull distributions of mineral oil at 3.5mm gap distance.

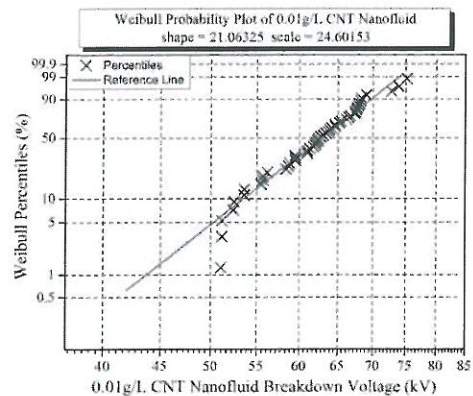


Fig 20 Weibull distributions of 0.01g/L CNT Nanofluid at 3.5mm gap distance.

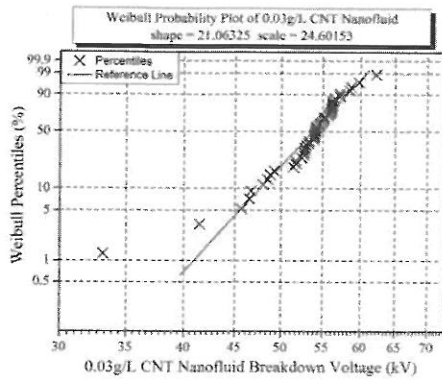


Fig 21 Weibull distributions of 0.03g/L CNT Nanofluid at 3.5mm gap distance.

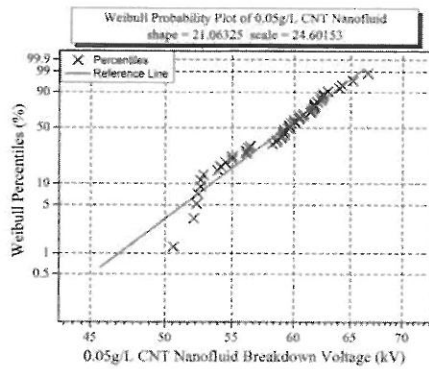


Fig 22 Weibull distributions of 0.05g/L CNT Nanofluid at 3.5mm gap distance.

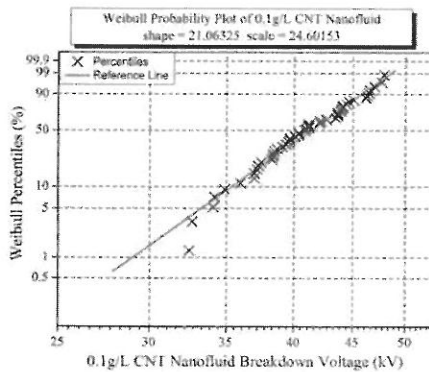


Fig 23 Weibull distributions of 0.1g/L CNT Nanofluid at 3.5mm gap distance.

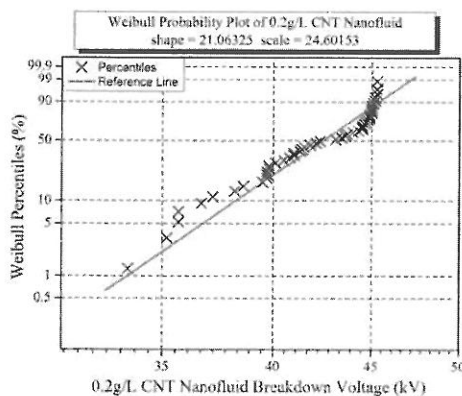


Fig 24 Weibull distributions of 0.2g/L CNT Nanofluid at 3.5mm gap distance.

TABLE VII  
PROBABILITY OF AC BREAKDOWN VOLTAGES (3.5MM GAP DISTANCE)

Oil Samples	P1 (%)	P50 (%)	P90 (%)
Mineral Oil	20.21	33.26	38.30
0.01g/L CNT Nanofluid	31.93	57.84	68.45
0.03g/L CNT Nanofluid	40.95	53.82	58.16
0.05g/L CNT Nanofluid	31.60	42.14	45.72
0.1g/L CNT Nanofluid	29.04	41.43	45.80
0.2g/L CNT Nanofluid	33.58	42.47	45.40

Looking into the modelling weibull results, the withstand voltage at low breakdown probability (1%), achieved an increase of 1.03 times than mineral oil. As for standard probability (50%) and high breakdown probability (90%) achieves increase of 2.74 and 1.79 times compared to Hyrax mineral oil. Based on the experimental analysis from three different gap distances, it reveals that the presence of CNT nanomaterials could enhance the breakdown strength of transformer oil. However, as the amount of CNTs increased, the performance gradually dropped. These might happened due to the behaviour of CNT nanomaterial which is highly entangled products and difficult to disperse uniformly in fluids [11], [12]. The suspension with stable condition may lead to better performance. Thus, the suitable de-agglomeration techniques for CNTs might be generating better dielectric fluid.

#### D. Comparison of AC Breakdown Voltage at Various Gap

Fig. 25 shows the behaviour of 1% probability of breakdown failure at three gap distances (1.5mm, 2.5mm and 3.5mm) for six types of oil samples including mineral oil as a reference.

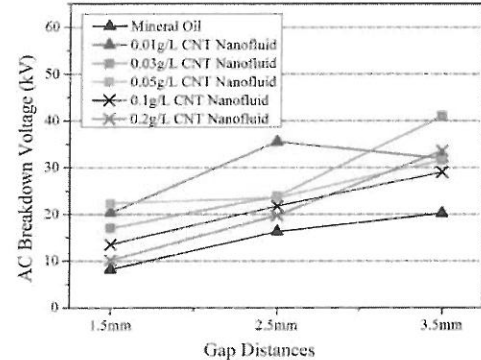


Fig. 25. Probabilities of 1% breakdown failure of mineral oil and CNT nanofluids at three gap distances.

The value of AC breakdown voltages for all types of oil increased along with gap distances except for 0.01g/L CNT nanofluid. The trend of AC breakdown voltages showed in the graph were also agreed by other researchers [13]. However, in case of 0.01g/L CNT nanofluid concentration, the graph trends dramatically began to decrease from 2.5mm to 3.5mm gap distances. This might be due to the inconsistent dispersion behaviour of CNTs in mineral oil. In addition, the distinction behaviour of CNT nanofluid was consequences of the morphed electro-dynamics within the oil caused by nanotubes, thereby produce different response from base mineral oil.

Based on overall perspective, the concentrations of CNT nanofluid affect the value of breakdown voltages obtained.

The amount of CNTs in mineral oil might affect the performances of AC breakdown voltages. The sound energy that applied into CNT nanofluid might not be enough due to larger amount of CNT nanofluid. Thus, CNT may not fully disperse and affect the stability of oil. However, based on 1% probability of breakdown voltage, all range of CNT nanofluids produced higher performance compare to Hyrax transformer mineral oil.

#### IV. CONCLUSIONS

This paper shows the comparison between Hyrax mineral oil as reference transformer oil and five different concentrations of CNT nanofluids. The sonication technique has been used in order to disperse CNT nanomaterials in the mineral oil. AC breakdown voltage test was performed at three gap distances by following proper procedure according to IEC 60156. Based on the experimental and statistical results, the following conclusions have been made:

- 1) For 1.5mm gap distance, all types of CNT nanofluids have enhance some improvement compare to mineral oil except for 0.2g/L CNT nanofluid. As for 2.5mm gap distance, 0.1g/L up to 0.05g/L CNT nanofluids achieved the same results except for 0.1g/L and 0.2g/L CNT nanofluids which have lower results compare to reference mineral oil. Lastly, for 3.5mm gap distance, the breakdown voltage performances for all range of CNT nanofluids achieved higher results compare to mineral oil. Thus, it can be conclude that CNT nanofluids have huge potential to enhance the performances of breakdown voltage in transformer application.
- 2) The concentrations of CNT nanofluids increased affect the breakdown voltage performances. It can be considered that the agglomeration of nanotubes might happened when CNTs approaches saturation level, and lead to reduction of the withstand voltage capability. Some researchers investigated that some surfactants are possible to help modify the nanomaterials in the insulating oil.
- 3) Based on the Weibull distribution analysis, 1% probability of AC breakdown voltages in CNT nanofluids (0.03g/L, 0.05g/L, 0.1g/L and 0.2g/L) increased along with the gap distances from 1.5mm to 3.5mm. The behaviour of CNT nanofluids breakdown voltages were figure out to be similar to the pattern of mineral oil. However, different cases for 0.01g/L CNT nanofluid which having fluctuated trend. The dispersion behaviour of CNTs in mineral oil might affect the stability of nanofluid and causes performance to drop at 3.5mm gap distance.

#### V. ACKNOWLEDGEMENTS

The authors would like to thank Ministry of Education and National Defence University of Malaysia for the funding under FRGS scheme (FRGS/2/2014/TK03/UPNM/02/2), (FRGS/1/2015/SG06/UPNM/03/3) and RAGS scheme (RAGS/1/2014/TK03/UPNM/1).

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