AC Breakdown Analysis of Synthesized Nanofluids for Transformer Insulation

SAMSON OPARANTI (sokikiola@gmail.com)
Ahmadu Bello University Zaria https://orcid.org/0000-0003-4190-4797
A.A. Khaleed
Ahmadu Bello University Zaria
A.A. Abdelmalik
Ahmadu Bello University Zaria

Research Article

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AC Breakdown Analysis of Synthesized Nanofluids for Transformer Insulation

Samson Okikiola Oparanti, Abubakar Abubakar Khaleed, Abdelghaffar Amoka Abdelmalik

Corresponding Author email: sooparanti@abu.edu.ng

Department of Physics

Ahmadu Bello University, Zaria

Zaria, NIGERIA

ABSTRACT

This work presents the effect of nanoparticles (Al_2O_3 and TiO_2) on methyl ester synthesized from palm kernel oil for oil-filled power equipment. It investigates the loss tangent, AC conductivity and AC breakdown strength of the methyl ester-based nanofluid. The surface of the nanoparticles was functionalized with oleic acid before dispersing it into methyl ester to modify the stability of the mixture. Scanning electron microscopy coupled with electron dispersive x-ray was done on the two nanoparticles to know the morphology and elemental composition of the nanoparticles. The preparation of nanofluids was achieved through the dispersion of 0.2, 0.4, 0.6, 0.8 and 1wt. % of nanoparticles into the ester. It was observed that the loading of the two nanoparticles reduces the loss tangent and the AC conductivity of methyl ester but with a pronounced enhancement in Al_2O_3 nanofluid. The Weibull statistical analysis of the breakdown data shows that the dispersion of the nanoparticles in the base fluid increases the characteristic breakdown strength of the ester with an optimum performance at 0.6 wt. %. The characteristic breakdown strength for TiO_2 and Al_2O_3 nanofluid is 60.6 kV and 64.1 kV respectively. The result revealed that Al_2O_3 nanofluid possesses the highest dielectric properties with low loss, low conductivity and high characteristic breakdown strength which makes it a better replacement for mineral insulating oil.

Keywords - Methyl ester, Nanofluids, Dielectric loss, AC Conductivity, AC characteristic breakdown, Weibull distribution

1 INTRODUCTION

Mineral oil has over the years being the desired insulating and cooling oil in oil-filled power transformers, cable and capacitors due to its unique properties over other transformer oil types especially when it comes to ageing [1]**.** This oil is inexpensive and commercially available in the market, however, it has been observed that leakage of transformer mineral oil causes environmental pollution. Due to the negative environmental impact and non-renewability of this oil, there was a quest for an environmentally friendly and sustainable insulating oil to prevent issues like global warming, acid rain and pollution [2]. Methyl ester gained attention as a dielectric liquid in the transformer application due to some outstanding characteristics over petroleum-derived insulating mineral. These characteristics include non-toxicity, biodegradability, high flash point and high thermal conductivity [3, 4]. It also has a high water retention capacity (hydrophilicity) compare to mineral oil and this help in protecting the cellulose paper whenever there is leakage of water in the transformer [5]. Furthermore, natural ester oil is environmentally friendly and have excellent dielectric performance [8]. The most commonly used ester oil is Palm fatty acid ester (PFAE) oil developed by Lion Corporation in 2006 for transformer insulation [7]. Researchers have continued to explore the applicability of natural ester as transformer oil to improve the quality of natural ester as an alternative for mineral insulating oil. In 2014, Abdelmalik modified palm kernel oil ester chemically. He reported high breakdown voltage compared to mineral oil [6]. Murad *et al.* did an investigation on the effect of moisture absorption on the dielectric behaviour of palm fatty acid ester. Their result revealed that PFAE oil has higher AC breakdown strength compared with mineral insulating oil [9]. Research was also extended to non-edible oil where Jatropha curcas was considered and it was reported to have the requirement of an insulating oil when subjected to refining process [10]. From the studies thus far, vegetable oil esters have demonstrated the enormous potential to be a substitute for mineral oils as insulating oil for transformer oil application. However, vegetable oil ester has two major hitches: high conductivity and low volume resistivity that over time leads to thermal breakdown of the transformer [11, 12]. To abate these hitches and improve the dielectric properties of vegetable oil ester, Nanofluids from vegetable ester oils have attracted great interest. Two techniques are used for the preparation of nanofluids: one-step method and two-step method [13]. The one-step method has been reported to be the best method as it reduces agglomeration during the dispersion of nanoparticles in the base oil simultaneously. However, this method is not commonly adopted in transformer oil-based nanofluid research since it is not economical. In the two-step method, the nanoparticle is chemically synthesized, dispersed into the base oil using a homogenizer or ultrasonicator. A well-blended nanofluid has been reported to have high electrical and thermal properties [16-18]. Several works have been done regarding the synthesis of nanofluid for transformer application. Jin *et al.*, 2012 investigated the effect of SiO_2 on mineral insulating oil and an enhancement in AC breakdown voltage was reported [15]. In 2014, Olmo *et al.*, [14] worked on dielectric enhancement of vegetable transformer oil using non-ferric oxide. They reported an enhancement in the dielectric properties of the oil. TiO_2, CuO and ZnO nanofluids were reported to have an increase in resistivity and a decrease in the loss factor. Madavan *et al.* investigated the effects of nanoparticles on characteristics of natural esters - based nanofluids using aluminium, boron nitrate (BN) and ferrous ferric oxide (Fe_3O_4). Their findings are quite promising due to an improvement in the performance of the nanofluids [18]. Characterization of natural ester-based nanofluid using iron oxide nanoparticle was examined by Peppas *et. al,* [19]. They found a decrease in dielectric loss and an increase in thermal conductivity in their nanofluid.

In this work, TiO_2 and Al_2O_3 nanofluids were developed. The choice of TiO_2 and Al_2O_3 nanoparticles is due to their excellent properties that include stability compared to pure metals, non-toxic nature, low cost, and easy production [5, 20]. Dielectric loss, conductivity and AC breakdown strength of the as-prepared nanofluids were investigated. Weibull statistical tool was used to analyze the breakdown strength from the obtained AC breakdown voltage data.

2 MATERIALS AND METHODS

2.1. Materials

The palm kernel oil used was locally purchased in Nigeria and methyl ester was synthesized from it. The Al_2O_3 and TiO_2 nanoparticles were purchased from Sky Spring Nanomaterials, Inc., USA.

The Tonsil fuller's earth was obtained from Parco enterprises Nig. Ltd. In addition, Filter paper Whatman number 1 and number 5, methanol, propane -2 -ol, Citric acid, NaOH, Oleic acid, Mineral oil (Shell Diala BX), and KOH were used in the experiment. The physicochemical properties of the nanoparticles are shown in Table 1 according to Sky Spring datasheet.

Table 1. Physical and chemical properties of nanoparticles from Sky Spring Datasheet

Nanoparticles	TiO_2	Al_2O_3
Form	Powder	Powder
Odour	Odourless	Odourless
Colour	White	White
Material type	Semiconductive	Insulating
Melting point (^oC)	2970	-
Boiling Point (^oC)	1840	-
SSA (m^2/g)	50-150	-
Purity (%)	99.5	99.99
True Density (g/cm3)	4.23	3.5-3.9

2.2. Oil Purification

The purification of the oil was done by heating 100ml of oil in a round bottom flask to 70^{o}C followed by the addition of proportional citric acid. The solution was thoroughly stirred for 15mins. Prepared NaOH solution was added at the same temperature to neutralize the oil from free fatty acid component. The mixture was then stirred for another 15 mins. The solution was oven-dried at 85^{o}C inside a vacuum oven for 30mins to reduce the water content. To the solution, an accurate proportion of Silica gel (1g) was added to further remove any traces of water molecule in the oil. The solution was thoroughly stirred to prevent silica agglomeration. Bleaching clay was further added to remove the coloured compound, metal and oxidation product. The mixture was stirred for 30 mins and then filtered with Whatman No. 1 and followed by No. 5.

2.3. Palm kernel oil ester preparation

400 ml of oil sample was measured in a flask and sodium methoxide solution prepared through dissolving 5.7g of NaOH into methanol was added into the oil at 60^{o}C. The solution was stirred for 1hr and the solution was then transferred into a separating funnel. The methyl ester was separated from the glycerol and the ester was washed with warm water to remove any leftover sodium hydroxide catalyst. The ester was oven dried for 2-3 hrs to remove remnant moisture in the sample.

2.4. Nanofluid preparation

The surface of the nanoparticles was coated using oleic acid and nanofluids were prepared with the nanoparticles in different percentage, ranging from 0.2 wt% - 1 wt% in the step of 0.2. The surface coating was to reduce the attraction between the nanoparticles by creating an intermolecular force that separate molecules from each other, thus, prevent agglomeration. The functionalization was done by dispersing 5 g of nanoparticle into 100 ml of ethanol. To the ethanol-nanoparticle solution, 0.25 ml of oleic acid was added and stirred for 2hrs. The solution was centrifuged and the nanoparticle was collected and oven-dry at 80^{o}C. The oleic acid-coated nanoparticles were dispersed into the methyl ester and stirred using a magnetic stirrer for 30 mins for optimum dispersion. Figure. 1 A-D shows pictures of the prepared samples. A is the purified oil, B is the methyl ester, C is the Al_2O_3 nanofluid and D is the TiO_2 nanofluid. Table 2 shows the sample description of the analyzed samples.

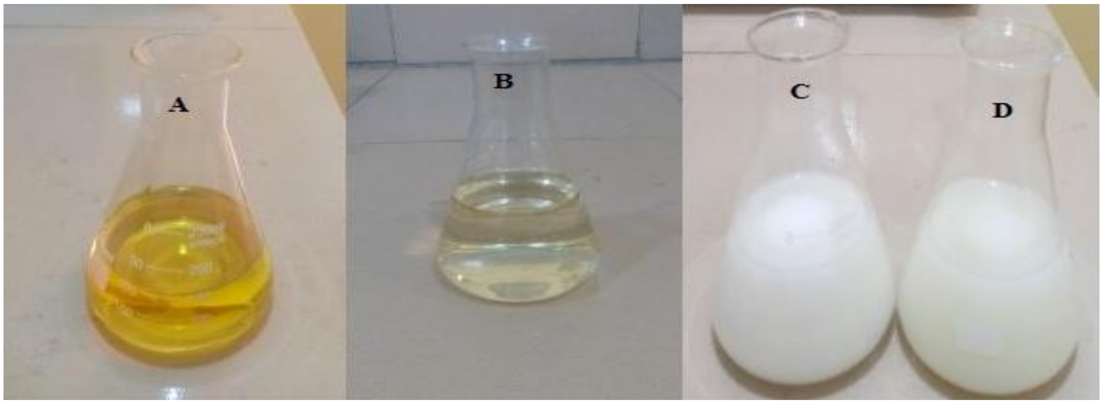

Figure 1 A. Purified Oil B. Methyl ester C. Al_2O_3 nanofluid D. TiO_2 nanofluid

Table 2. Sample Description

Sample code	Description	Sample code	Description
MO	Mineral oil	ME	Methyl ester
PPKO	Palm kernel oil	MET1	Ester + 0.2wt% TiO_2 NP
MEA1	Ester + 0.2wt% Al_2O_3 NP	MET2	Ester + 0.4wt% TiO_2 NP
MEA2	Ester + 0.4wt% Al_2O_3 NP	MET3	Ester + 0.6wt% TiO_2 NP
MEA3	Ester + 0.6wt% Al_2O_3 NP	MET4	Ester + 0.8wt% TiO_2 NP
MEA4	Ester + 0.8wt% Al_2O_3 NP	MET5	Ester + 1wt% TiO_2 NP
MEA5	Ester + 1wt% Al_2O_3 NP	-	-

2.5.1. SEM-EDX

The nanoparticles were analyzed using an ultra-high vacuum and high-resolution scanning electron microscope (SEM) integrated with electron dispersive X-ray analysis (EDX). Both the morphology of the nanoparticles and the elemental compositions were determined using ZEISS EVO LS10 operating at 20 kV.

2.5.2 Dielectric measurement.

The dielectric loss of MO, ester oil and NFs were measured according to IEC 60247-2004, using Rohde & Schwarz HM8118 Programmable LCR BRIDGE. The set-up consists of two parallel plates electrodes test cell of diameter 30 mm and a gap of 2.5 mm. Both electrodes were fully immersed in samples and the capacitance and dielectric loss were measured at power frequency (60 Hz) at 27^{o}C.

The real permittivity,ε', which is related to the energy stored within the medium and ε'', the imaginary permittivity which is related to the dissipation of energy within the medium is related to the loss tangent with the equation;

$$\varepsilon'' = \varepsilon' * tan\delta \quad (1)$$

Where δ is the loss angle and is the angle between the effective current and displacement current.

The electrical conductivity of the samples was determined using the equation;

$$\sigma_{ac} = \omega \varepsilon_o \varepsilon'' \qquad (2)$$

Where σ is the conductivity in Sm^{-1}, $\omega = 2\pi f$ is angular frequency, ε_o is the permittivity of free space, ε'' is the dielectric loss factor.

2.5.3. AC and Weibull plot Analysis

The dielectric breakdown voltage of the samples was measured in accordance with the ASTM D1816 standard [2]. An automated test kit ‘Insulating oil Dielectric strength tester’ with model FS2080 was used to determine the dielectric breakdown of each sample. The electrode of the test kit has a spherical mushroom shape with a gap spacing of 2.5 mm. 250 ml of oil sample was used for each breakdown. The test was performed by increasing the supply voltage step wisely at a rate of 1 kV/s until breakdown occurs. The AC breakdown voltage of the samples was analyzed using Weibull statistics. For this analysis, the two-parameter Weibull plot was used and the breakdown probabilities were determined. For any random variable x, the cumulative distribution function of Weibull distribution is defined as;

$$F(x) = 1\text{-}\exp\left(\frac{-x}{\alpha}\right)^{\beta} \qquad (3)$$

Where x is the breakdown voltage, β is the shape parameter that is related to failure rate and α is the characteristic breakdown strength or scale parameter that is related to the probability of 63.2%.

3. Result and Discussion

3.1 SEM-EDX Analysis

The elemental composition and the surface morphology of TiO_2 and Al_2O_3 nanoparticles were studied using ultra-high vacuum-high-resolution SEM integrated with EDX. Figure 2 and 3 show the micrograph and elemental composition of TiO_2 and Al_2O_3 nanoparticles, respectively. The micrographs of both nanoparticles displayed uniform dispersion of the nanoparticles with little cluster and little variation in shapes with a high percentage of spherical related shapes. Some noticeable variation in shape may be due to clustering of some of the particles. Investigation using electron dispersive X-ray further confirmed the purity and the elemental composition of the nanoparticles as illustrated in Figure 2 and 3.

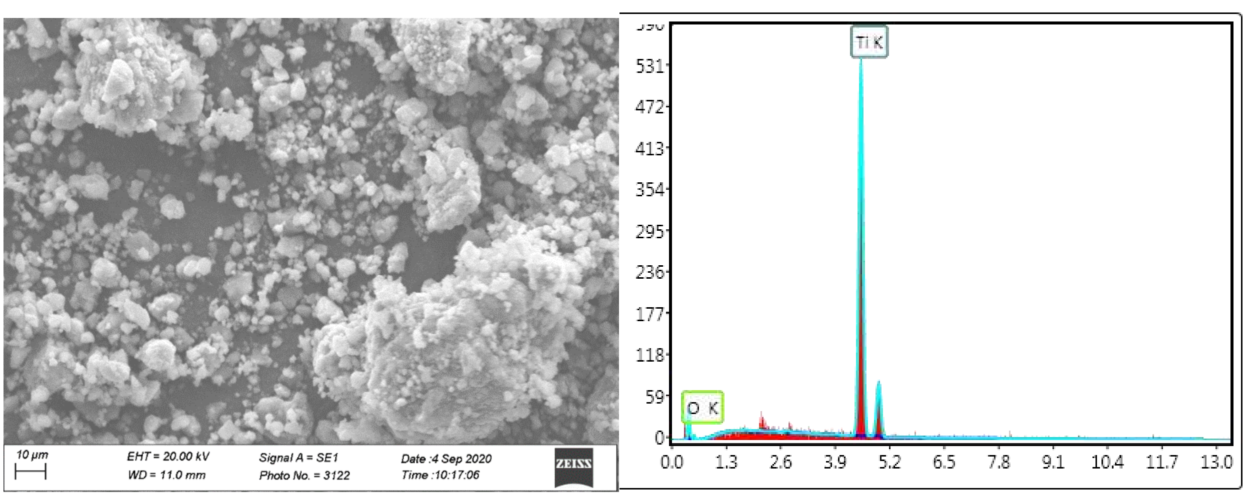

Figure 2. Micrograph and EDX of TiO_2 nanoparticle.

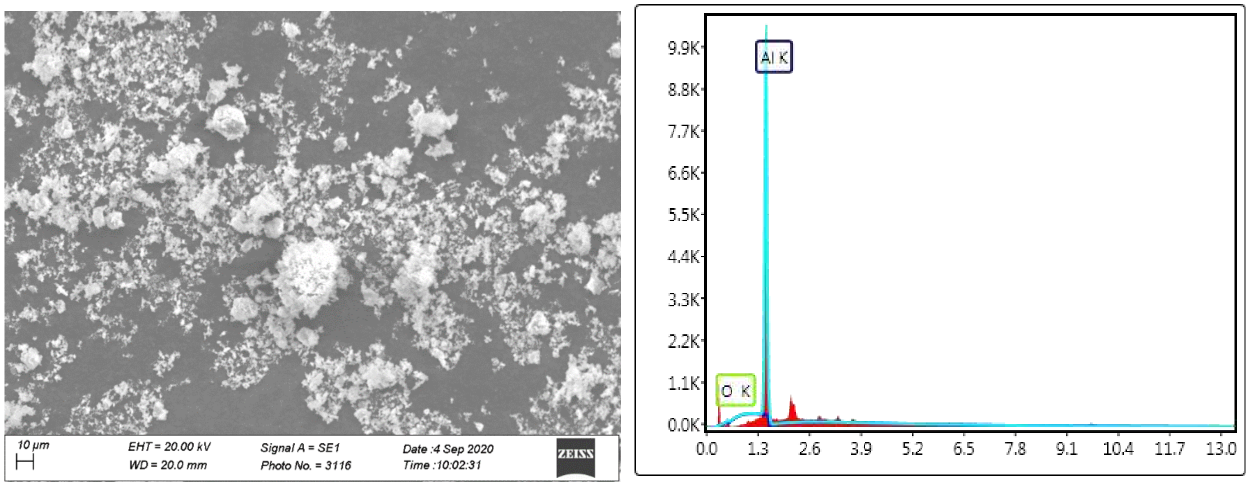

Fig.3. Micrograph and EDX of Al_2O_3 nanoparticle.

3.2 Dielectric loss and AC conductivity

The dielectric loss of the samples was determined at a power frequency of 60 Hz. Table 3 shows the dielectric loss of MO, ME, TiO_2-nanofluids and Al_2O_3-nanofluids. It was observed that after the transesterification process, the loss in the methyl oil ester increased which can be attributed to some dissociated chemical used in the process. The dielectric loss of mineral oil was observed to be lower than that of the purified oil and that of the ester. A perfect insulating material is expected to have zero conductivity and no loss but a perfect insulator hardly exist. The dielectric loss of mineral oil can be attributed to polarization phenomena in the liquid and conduction of ionic impurities in the liquid. Thus, the dielectric loss in mineral oil is a combination of polarization and conduction processes. Table 4 shows the conductivity of all the samples at 60 Hz**.** The dielectric loss and AC conductivity results of mineral oil obtained in this work are similar to the one reported in the technical data sheet of Shell Diala BX. The oil was reported to have a dielectric loss of 0.002 at 40-60 Hz that agrees to 0.00115 obtained in this work. The conductivity measured in this work is also close to the one in the datasheet at 25°C which is of the order 10^{-12}. The results are also similar to the values reported by Abdelmalik [8]. The dielectric loss and conductivity of natural ester obtained by Umar *et al*., [24] are of the order 10^{-2} and 10^{-10} respectively. This is similar to the result obtained for natural ester in this work. The result comparison with literature was used to affirm the accuracy of the set-up before further characterization of the nanofluids. The dispersion of the nanoparticles in the oil was observed to have led to a reduced dielectric loss in the methyl ester. A similar observation was made for the two nanoparticles in the methyl ester. The progressive loading of nanoparticles from 0.2wt% - 1wt% led to a reduction in conduction rate by trapping and de-trapping of the dissociated electron in the methyl ester by the nanoparticles and consequently reduce the dielectric loss. The aligned layers of the nanoparticle also create a strong intermolecular structure which helps in the trapping of electrons and mobile ions between the inter-particle zones, this also reduces the conduction and consequently reduces the dielectric loss [23]. While the dispersion of the two nanoparticles led to reduced dielectric loss, the reduction in the dielectric loss is more pronounced in Al_2O_3-nanofluid when compared with TiO_2-nanofluid**.** This may be attributed to dielectric nature of Al_2O_3 nanoparticle which requires more electron to get excited before allowing a release of an electron to the next neighboring nanoparticle thereby reducing conductivity that consequently reduces the loss. The AC conductivity of each sample was obtained using equation (2). Since the conductivity is having a direct relationship with dielectric loss, a corresponding decrease in the conductivity of the ester was observed across the loading of nanoparticles. The obtained data revealed that Al_2O_3-nanofluid would likely serve better as an insulating fluid for oil-filled power equipment when considering the loss and the conductivity.

Table 3. The dielectric loss of MO, PPKO, ME and nanofluids at 60 Hz

Sample	MO	PPKO	ME	MEA1	MEA2	MEA3	MEA4
Dielectric Loss (tan δ)	0.00115	0.00631	0.044	0.00221	0.00152	0.00129	0.00083
Sample	MEA5	MET1	MET2	MET3	MET4	MET5	-
Dielectric Loss (tan δ)	0.00051	0.00432	0.0034	0.00264	0.00212	0.00144	-

Table 4. AC conductivity of MO, PPKO, ME and nanofluids at 60 Hz

Sample	MO	PPKO	ME	MEA1	MEA2	MEA3	MEA4
AC Conductivity (S/m)	7.78×10^{-12}	7.46×10^{-11}	4.71×10^{-10}	2.97×10^{-11}	2.35×10^{-11}	2.24×10^{-11}	1.65×10^{-11}
Sample	MEA5	MET1	MET2	MET3	MET4	MET5	-
AC Conductivity (S/m)	1.11×10^{-11}	6.35×10^{-11}	5.77×10^{-11}	5.32×10^{-11}	4.93×10^{-11}	3.71×10^{-11}	-

3.3 AC Breakdown Test

Breakdown phenomenon in insulating materials is a statistical event. Therefore, the characterization of the breakdown field strength of insulating materials requires several measurements on the sample. Twelve (12) AC breakdown was performed on each sample of MO, PPKO, ME, Ester-based TiO_2 nanofluids and Al_2O_3 nanofluids. The variation in the values of breakdown voltage for each sample of oil is due to the random distribution of the weakest paths. Weibull statistics is based on extreme-value statistics and it fails when the weakest link fails. It is the most commonly used statistics in high voltage materials/system failure and it is adopted in this analysis. One interesting feature of Weibull statistics is the fact that it can be used to analyze small sample data. Figure. 4 to 8 shows the Weibull plot of MO, PPKO, ME and the prepared nanofluids. Figure 4 presents the Weibull plot of PPKO and ME. The two samples have nearly the same slope but PPKO has higher breakdown values as compare with its methyl ester, an indication they have a similar distribution. Figure 5 to 7 also indicate that MO, methyl and its nanofluid have a similar distribution. Figure 8 present the Weibull plot of the fluids with optimum breakdown values. The plots for the 0.6wt% Al_2O_3 and TiO_2 nanofluids show that the breakdown data falls within the same range of values.

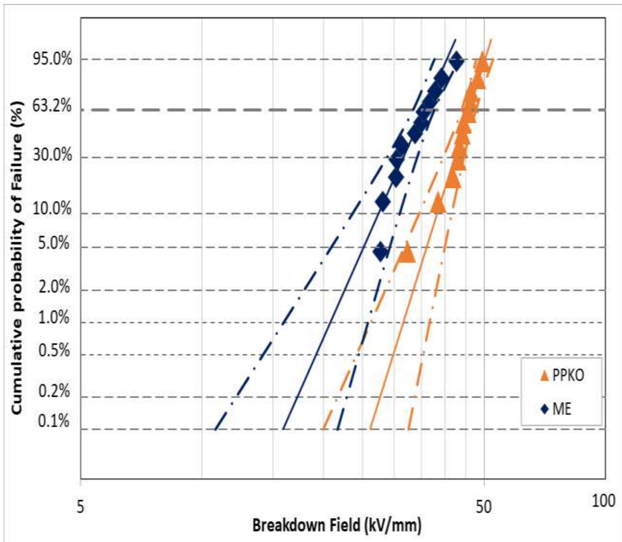

Fig. 4. Two-parameter Weibull plot of the AC Breakdown voltage for Purified Palm Kernel Oil and Methyl ester.

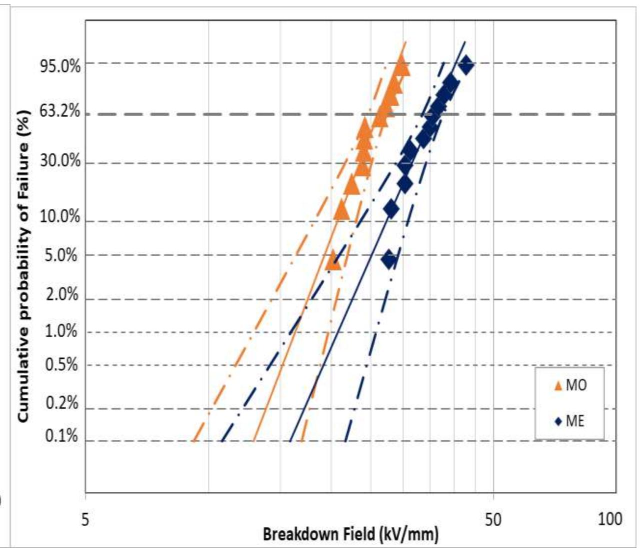

Fig. 5. Two-parameter Weibull plot of the AC breakdown voltage for Mineral oil and Methyl ester

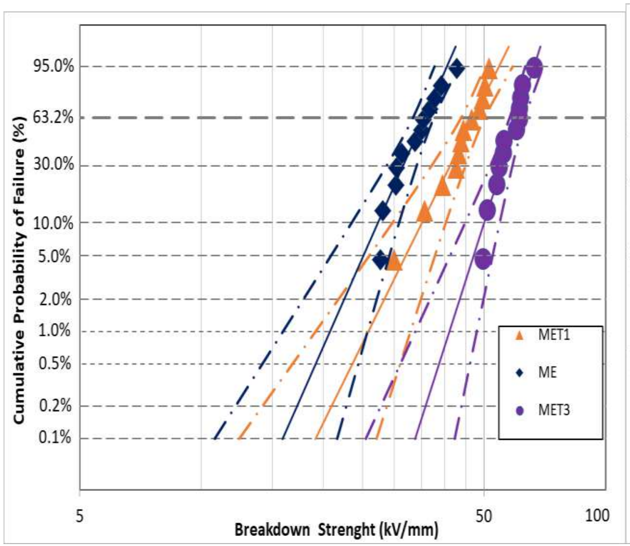

Fig.6. Two-parameter Weibull plot of the AC breakdown voltage for Methyl ester, 0.2wt. % and 0.6wt. % of TiO_2 Ester- based nanofluids.

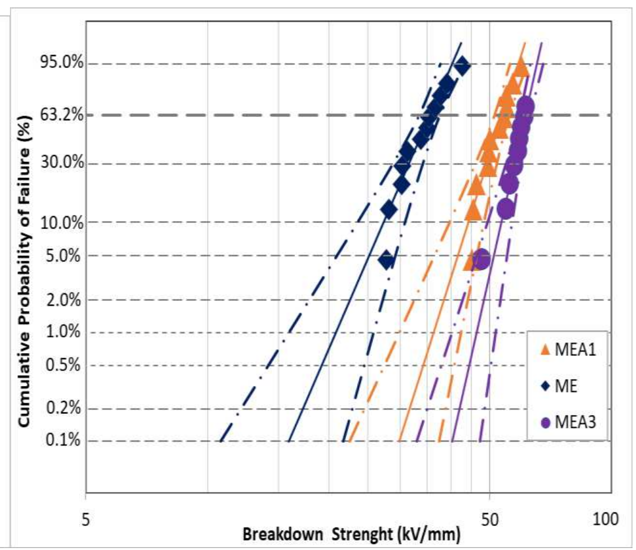

Fig. 7. Two-parameter Weibull plot of the AC breakdown voltage for Methyl ester, 0.2wt. % and 0.6wt. % of Al_2O_3 Ester- based nanofluids.

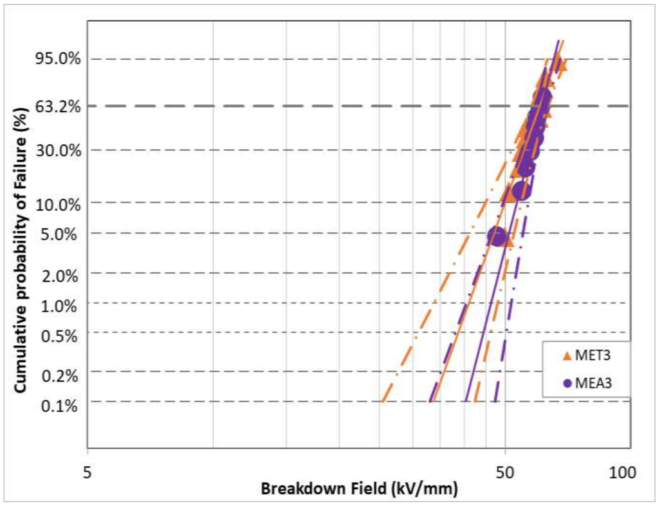

Fig. 8. Two-parameter Weibull plot of the AC breakdown voltage for 0.6wt.% of TiO_2 and Al_2O_3 Ester-based nanofluids.

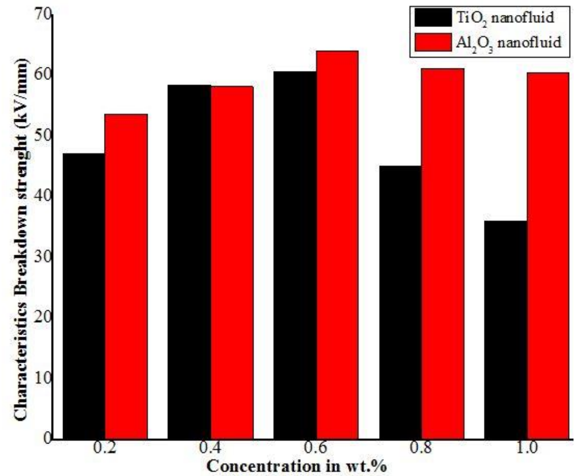

Fig. 9. Characteristic breakdown strength of TiO_2 and Al_2O_3 nanofluids

The scale parameter (α), shape parameter (β) and correlation coefficient (ρ) for MO, PPKO, ME, Ester-based TiO_2 and Al_2O_3 nanofluids based on the two-scale parameter Weibull Plots are summarized in Table 5. It can be observed from the table that the correlation coefficients of the breakdown data when fitted in Weibull function, equation (3), are greater than $R^2 = 0.918$ for 10 breakdowns [21]. Judging from the correlation coefficient values which are close to 1, it is evident that there is a strong positive correlation between the Weibull probability and AC breakdown strength for all samples. The high values of the shape parameter for all the samples show that there is a low dispersion in the breakdown data of every sample. The mean normal distribution breakdown strength of mineral oil (Shell Diala) and palm kernel oil methyl ester was compared with the literature. The mean breakdown strength of mineral oil was obtained to be 24.5kV with a standard deviation of 2.24 kV (9%). This result is similar to the one obtained by [25] for Diala D (26.4kV and 1.9kV (7%)). Also, for palm kernel oil methyl ester, the average breakdown strength was obtained to be 32 kV with standard deviation of 3.2 kV (10%). This value appeared better when compared with the obtained result by [23] for natural ester (31 kV). It can be observed from table 5 that mineral oil has the lowest breakdown strength with a value of 26.03 kV/mm. For the vegetable oil insulating fluid (PPKO), the breakdown strength was observed to be 45.91 kV and it is 43.3% greater than the breakdown strength of mineral insulating oil. For effective cooling and proper circulation of the oil in the transformer, transesterification was done and the glycerol which is the backbone of the methyl ester was removed. After the transesterification, the breakdown strength of the PKO methyl ester was obtained to be 35.56 kV which indicates that the removal of glycerol led to the reduction of the AC breakdown strength of the seed oil by 22.5%. However, despite the reduction in breakdown strength after the chemical modification, methyl ester characteristic breakdown strength is still 26.8% greater than that of the mineral oil which indicated that the sustainable alternative oil is a viable alternative to mineral oil. To study the influence of the nanoparticles on the base oil, the loading of the nanoparticles was done in the range of 0.2wt. % to 1wt. % in the step of two to observe the effect of the nanoparticle on the insulating performance of the green alternative. The addition of nanoparticles (semiconducting and insulating nanoparticles) was observed to have increased the characteristic breakdown strength of the base oil with optimum performance at 0.6wt. %. The dispersion of nanoparticles beyond 0.6wt% resulted in a decrease in breakdown strength of the nanofluid samples. This can be attributed to the decrease in inter-particle distance and a reduction in the potential width of the double layers. This may have led to the overlapping of the nanoparticles which when exposed to a high electric field, may get charged and then bridge the flow of electrons.

Table 5. Shape parameter, scale parameter and correlation coefficient obtained from the two-parameter Weibull plots.

Samples	N	Characteristic Breakdown strength, α (kV/mm)	95% Confidence bound for α (kV/mm)	shape parameter, β	95% Confidence bound for β	ρ Correlation Coefficient
MO	12	26.0	24.64 – 27.32	9.83	6.41 – 16. 97	0.959
PPKO	12	45.9	43.94 – 47.72	12.26	7.99 – 21.16	0.963
ME	12	35.6	33.40 – 37.59	8.56	5.58 -14.77	0.944
MEA1	12	53.7	51.27 -55.88	11.76	7.66- 20.29	0.927
MEA2	12	58.2	55.78 – 60.33	12.90	8.41 – 22.26	0.964
MEA3	12	64.1	59.57 – 68.32	7.38	4.81 – 12.74	0.970
MEA4	12	61.1	59.19 – 62.92	16.57	10.80 – 28.59	0.971
MEA5	12	60.5	57.21 – 63.56	9.62	6.27 – 16.60	0.979
MET1	12	47.1	43.92 – 50.12	7.65	4.98 – 13.20	0.988
MET2	12	58.4	55.08 – 61.49	9.19	5.99 – 15.87	0.946
MET3	12	60.6	57.86 – 63.03	11.81	7.69 – 20.38	0.954
MET4	12	45.0	43.65 – 46.19	17.87	11.64 – 30.84	0.966
MET5	12	36.0	34.05 – 37.78	9.73	6.34 – 16.80	0.990

Table 6. Weibull probability of the AC breakdown voltage for all oil samples

Weibull Probability (%)	AC breakdown voltage (kV)							
	MO	PPKO	ME	MEA1	MEA2	MEA3	MEA4	MEA5
1	16.30	31.54	20.78	36.29	40.71	42.36	37.50	36.30
5	19.24	36.03	35.6	41.69	46.19	47.85	44.43	43.60
10	20.70	38.21	27.34	44.32	48.84	49.24	47.21	45.14
30	23.44	42.20	31.53	49.17	53.69	55.72	54.36	52.73
63.2	26.03	45.91	35.56	53.67	58.15	64.07	61.50	60.50

Weibull Probability (%)	AC breakdown voltage (kV)				
	MET1	MET2	MET3	MET4	MET5
1	25.82	35.41	41.01	34.77	22.43
5	31.95	42.27	43.08	38.09	26.52
10	35.11	45.72	46.94	39.66	28.55
30	41.17	52.20	55.49	42.46	32.36
63.2	47.11	58.40	60.6	44.98	35.98

The characteristics AC breakdown strength of all the samples for the selected probability of failures can be seen in Table 6.

Since unforeseen failure at low voltage is inevitable, the breakdown voltage at the lowest probability (1%) for each sample was also considered. It was observed that the breakdown strength of the prepared nanofluids at the lowest probability are better than the breakdown voltage of both mineral oil and methyl ester with Al_2O_3 nanofluids having a remarkable value. At 0.6wt% of Al_2O_3 nanofluid, an exceptional value of breakdown voltage (42.36 kV/mm) obtained at 1% probability demonstrates high operating reliability of the fluid.

Figure 9 compared the characteristic breakdown strength of the prepared nanofluids from TiO_2 and Al_2O_3 nanoparticles. The dispersion of TiO_2 and Al_2O_3 nanoparticles in the base fluid increase the breakdown strength by 41.3% and 44.5% respectively. This indicates that Al_2O_3 nanoparticle increases the AC breakdown voltage more than TiO_2. It has been reported that semiconducting and insulating nanoparticle produces shallow electron traps which captured the fast-moving electrons and convert them to a slower electron through repeated tapping and de-trapping when there is mobility of electron from high electric field to low electric field. The addition of TiO_2 nanoparticle to the ester helps to reduce the transport of electron in the nanofluid by repeated trapping and de-trapping mechanism with the aid of the shallow trap created. More shallow traps are created in insulating nanoparticle as compare with semiconducting nanoparticle. This may be responsible for the higher breakdown strength of the nanofluid sample containing Al_2O_3 nanoparticle [22]. This trap helps in converting fast electrons created by high electric field to slow electrons through the hopping process. The oil dielectric strength is increased through this hopping process by decreasing the speed of the electrons and also prevents the accumulation of space charges in the oil. The result obtained from this work when considering the effect of the nanoparticles can be compared with the one reported in the literatures. Makmud *et al*. reported that TiO_2 nanofluid from natural ester has breakdown voltage around 53 kV/mm at 1g/L concentration which is less than optimum breakdown voltage obtained for TiO_2 nanofluid in this work (60.6 kV/mm) [23]. Also, Mohamad *et al*. reported on characteristic breakdown strength of palm fatty acid ester -Al_2O_3 nanofluid to be 36.87 kV/mm whereas, the result obtained in this work at optimum performance is 64.1 kV/mm [22]. This indicates that the developed nanofluid is compared well with previously reported results and have more breakdown strength. It can be deduced from the results that the nanofluids from the two nanoparticles have good dielectric properties. Al_2O_3 nanofluid will likely serve better as an insulating fluid compared with TiO_2 nanofluid.

4 CONCLUSION

In this work, synthesis of natural ester was done and the influence of semiconducting and insulating nanoparticles on the dielectric loss, conductivity and AC breakdown voltage of the prepared natural ester was studied. The dielectric loss and the conductivity of samples at every loading of nanoparticles reduces with increase in loading. This may be attributed to the trapping and de-trapping of the mobile electron and ions in the oil. An increase in AC breakdown strength was observed with loading of nanoparticles from 0.2wt% with an optimum performance at 0.6wt% for both TiO_2 and Al_2O_3 nanoparticle. The reduction in the value of AC breakdown voltage after 0.6wt% may be attributed to the higher percentage of nanoparticle which causes a reduction in inter-particle distance and consequently, led to conduction which eventually reduces dielectric breakdown voltage. This work revealed that the dispersion of nanoparticles in palm kernel oil ester resulted in the reduction of the dielectric loss and AC conductivity and improved breakdown strength at 0.6wt% loading. Meanwhile, the nanofluid with Al_2O_3 nanoparticle appears to perform better as an insulating material in oil-filled high voltage equipment.

Declarations

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Conflicts of interest: The authors declare no conflict of interest

Availability of data and material: Not applicable

Code availability: Not applicable

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent for publication: Not applicable

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Figures

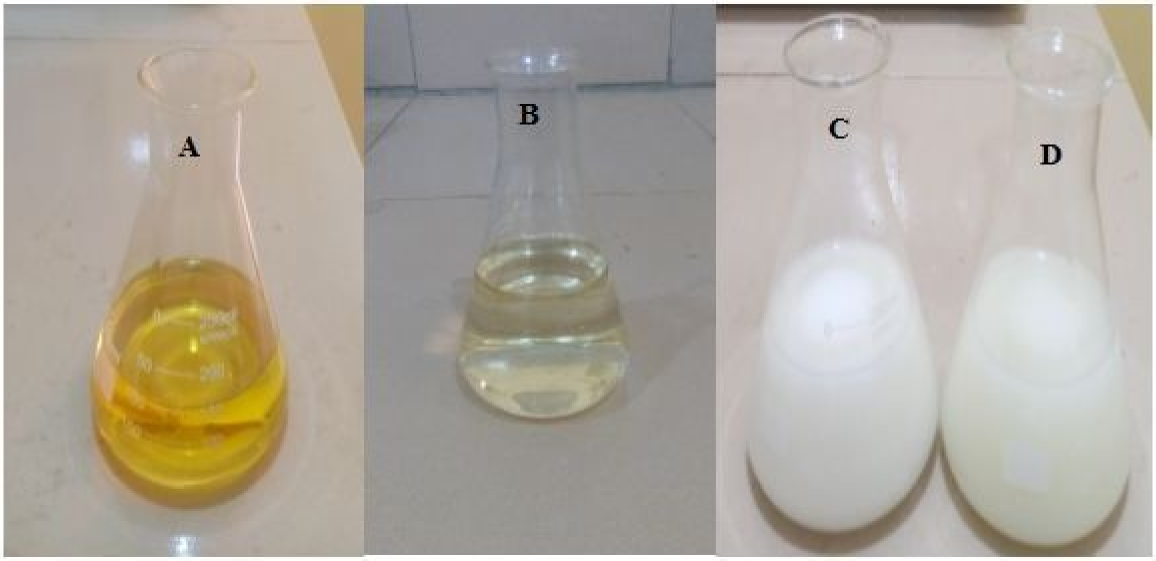

Figure 1

A. Purified Oil B. Methyl ester C. Al2O3 nanofluid D. TiO2 nanofluid

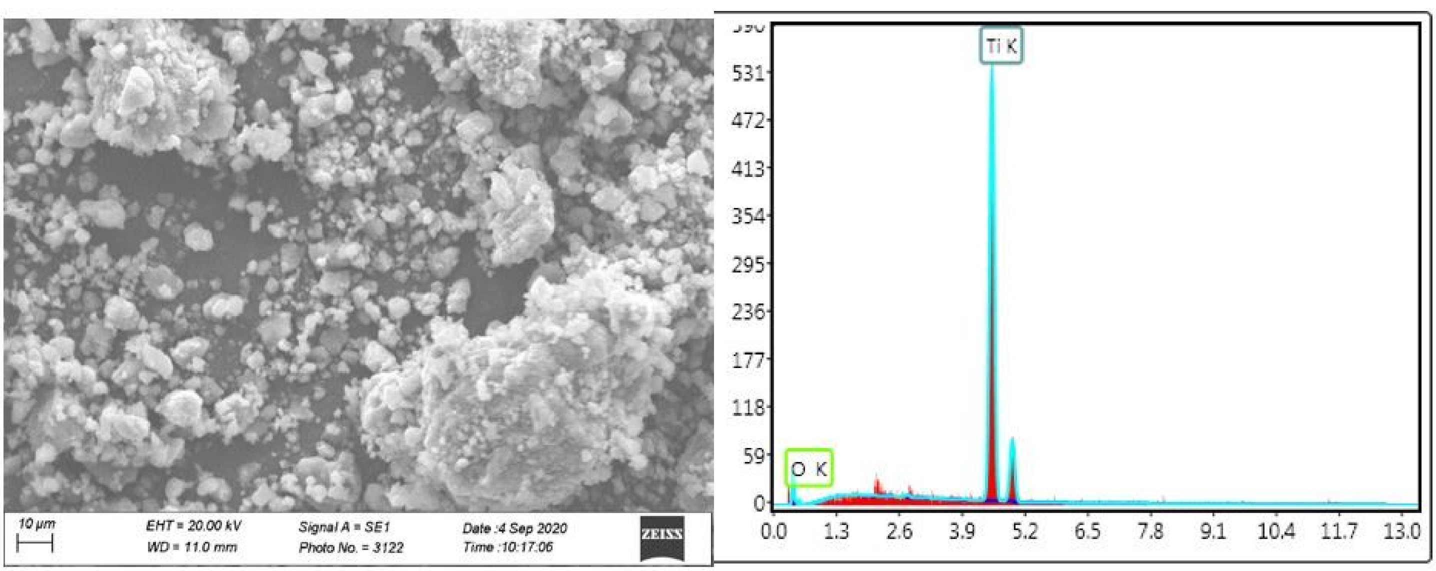

Figure 2

Micrograph and EDX of TiO2 nanoparticle.

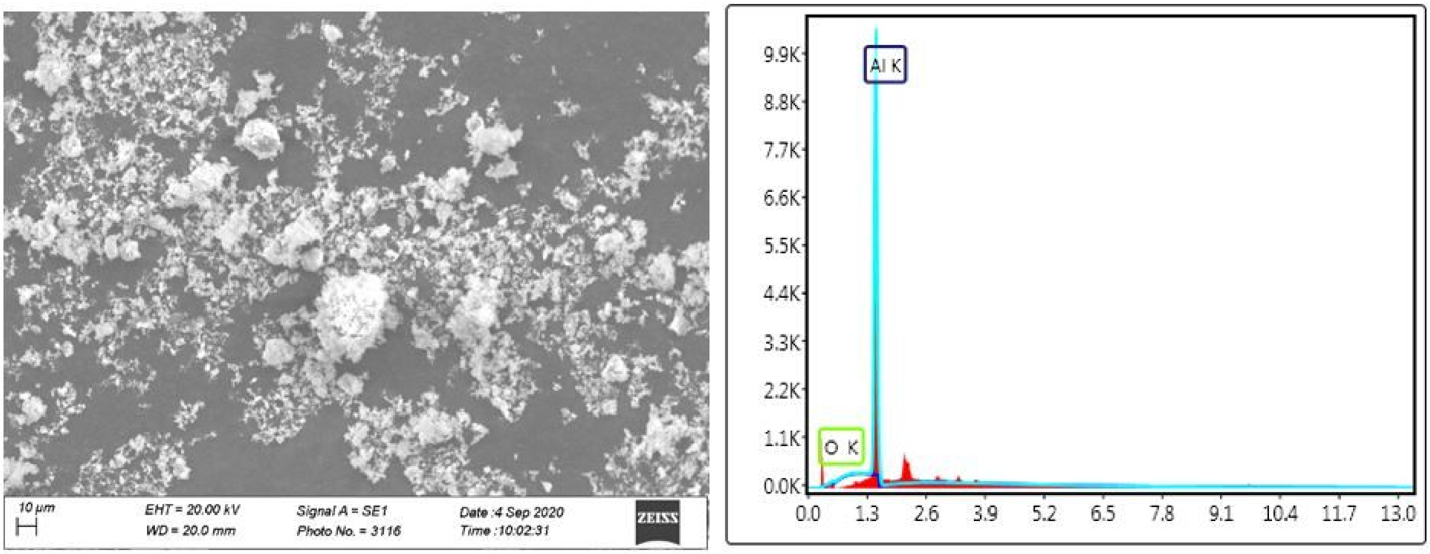

Figure 3

Micrograph and EDX of Al2O3 nanoparticle.

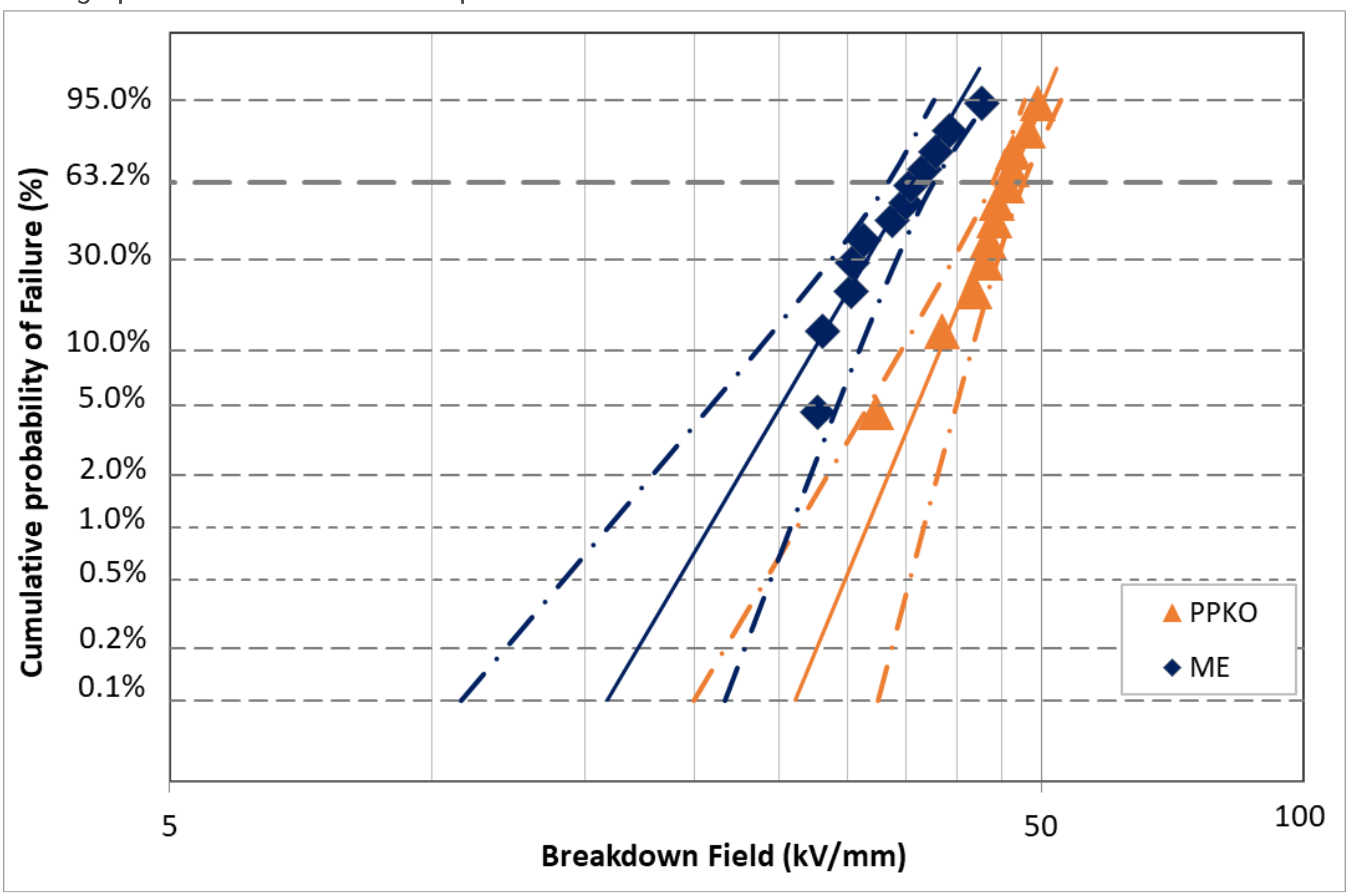

Figure 4

Two-parameter Weibull plot of the AC Breakdown voltage for Purified Palm Kernel Oil and Methyl ester.

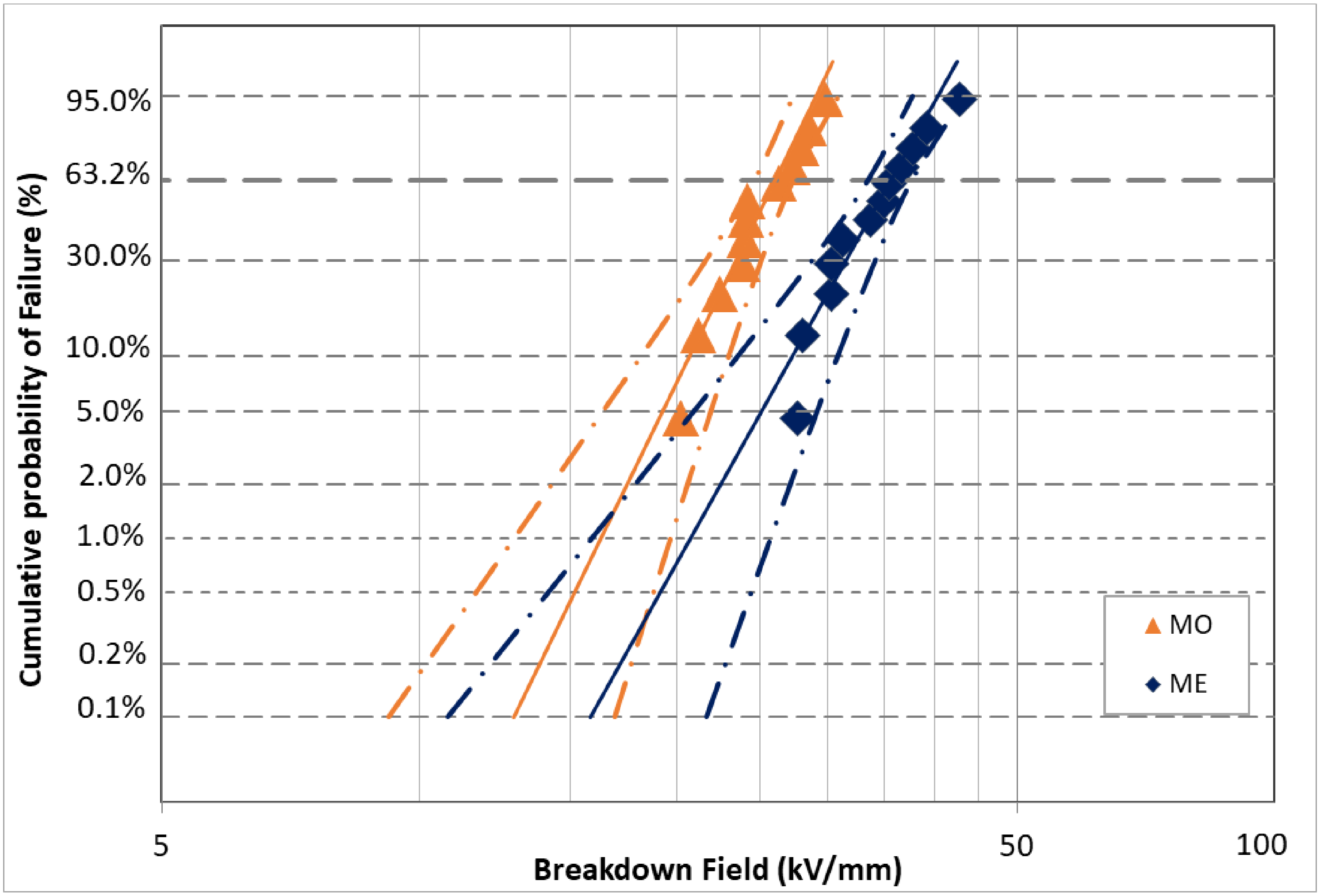

Figure 5

Two-parameter Weibull plot of the AC breakdown voltage for Mineral oil and Methyl ester

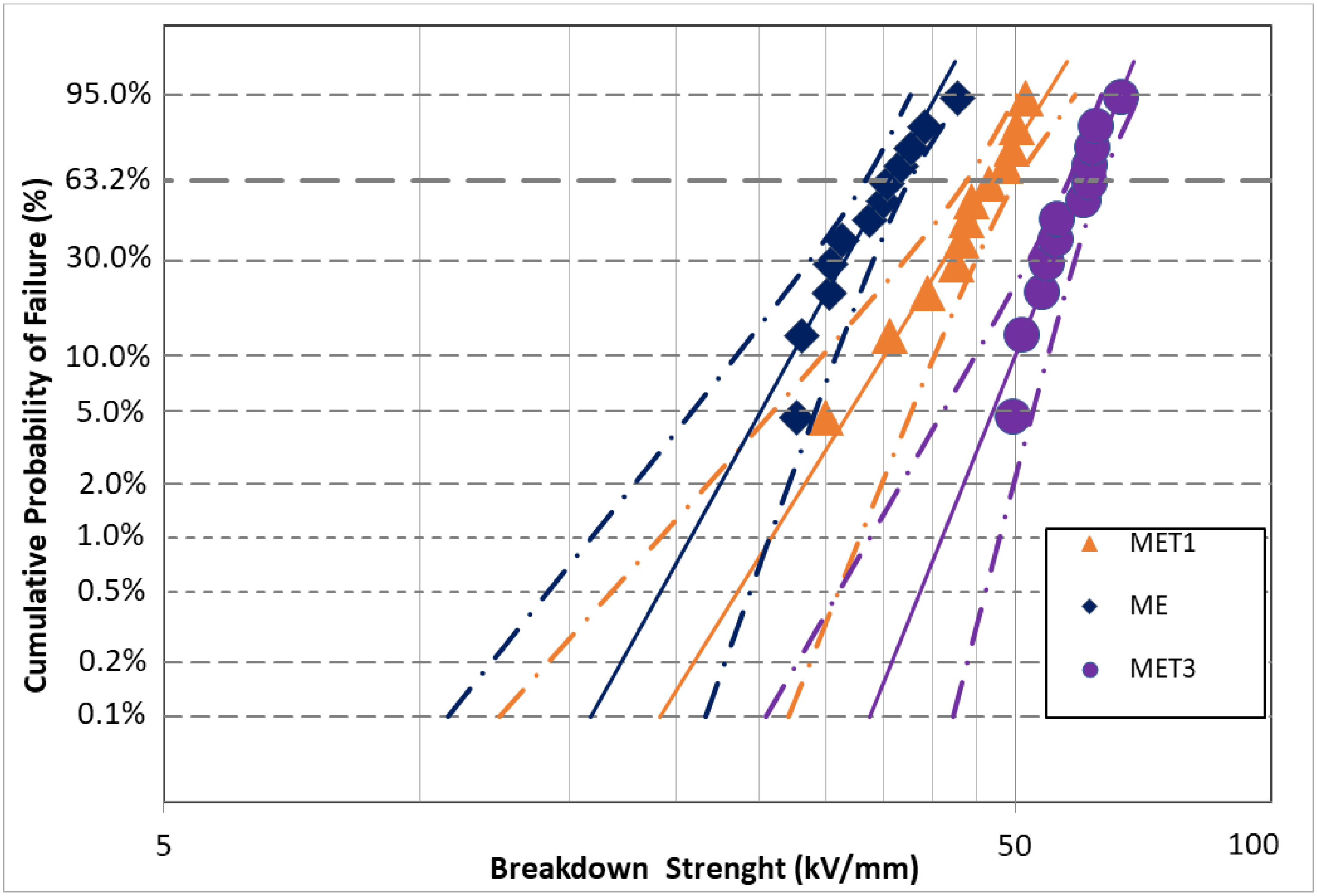

Figure 6

Two-parameter Weibull plot of the AC breakdown voltage for Methyl ester, 0.2wt. % and 0.6wt. % of TiO2 Ester- based nanofluids.

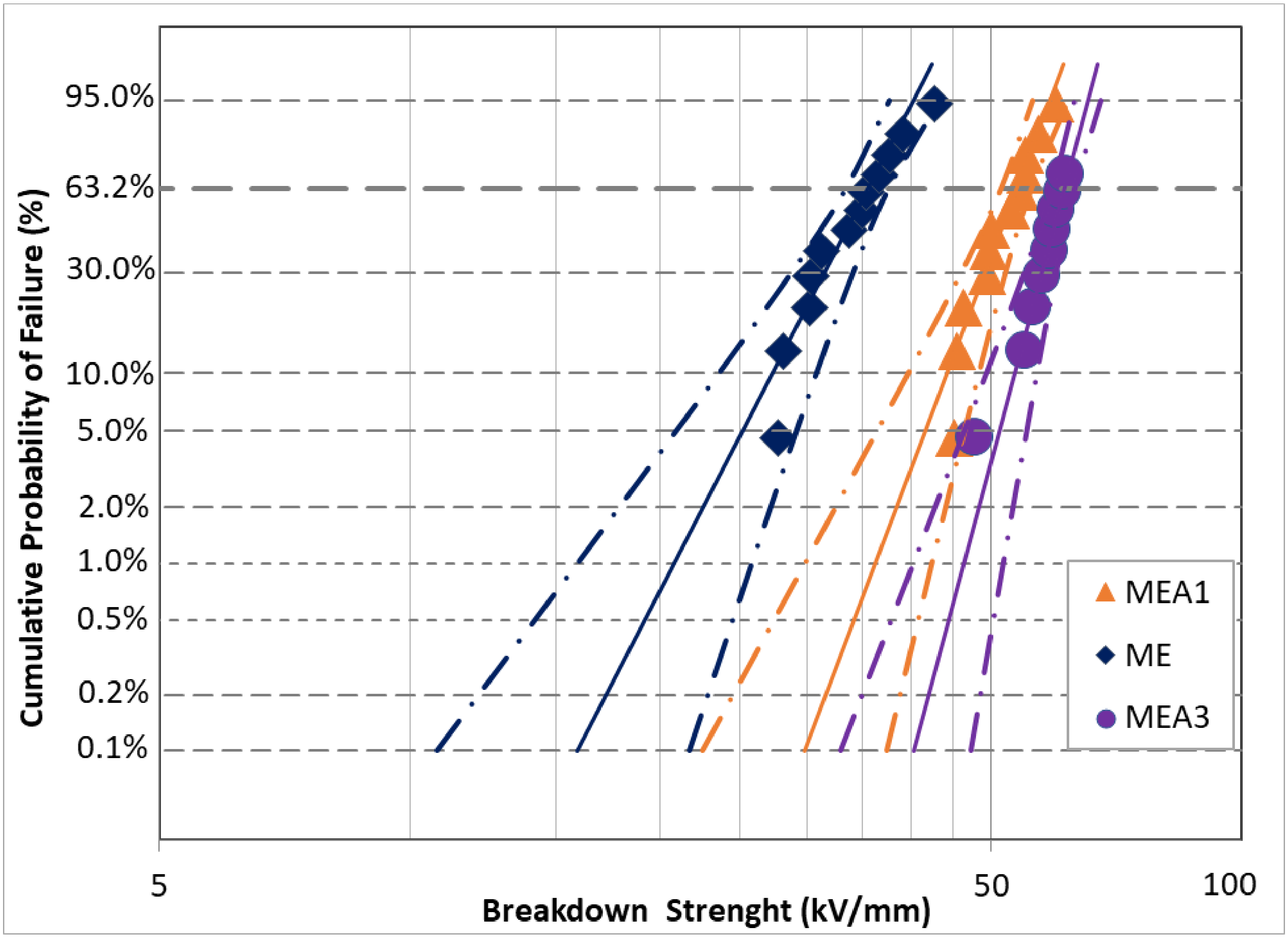

Figure 7

Two-parameter Weibull plot of the AC breakdown voltage for Methyl ester, 0.2wt. % and 0.6wt. % of Al2O3 Ester- based nanofluids.

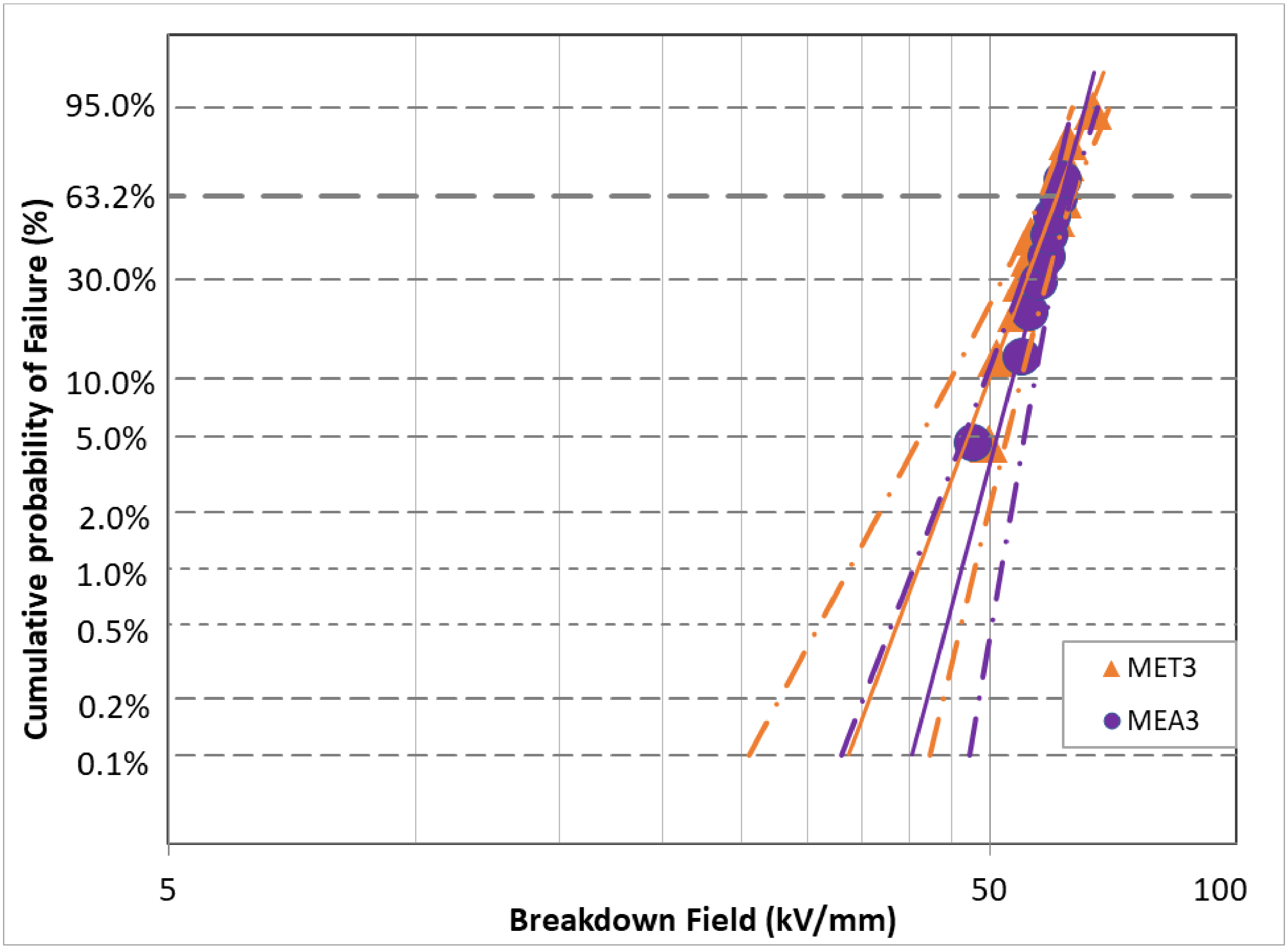

Figure 8

Two-parameter Weibull plot of the AC breakdown voltage for 0.6wt.% of TiO2 and Al2O3 Ester-based nanofluids.

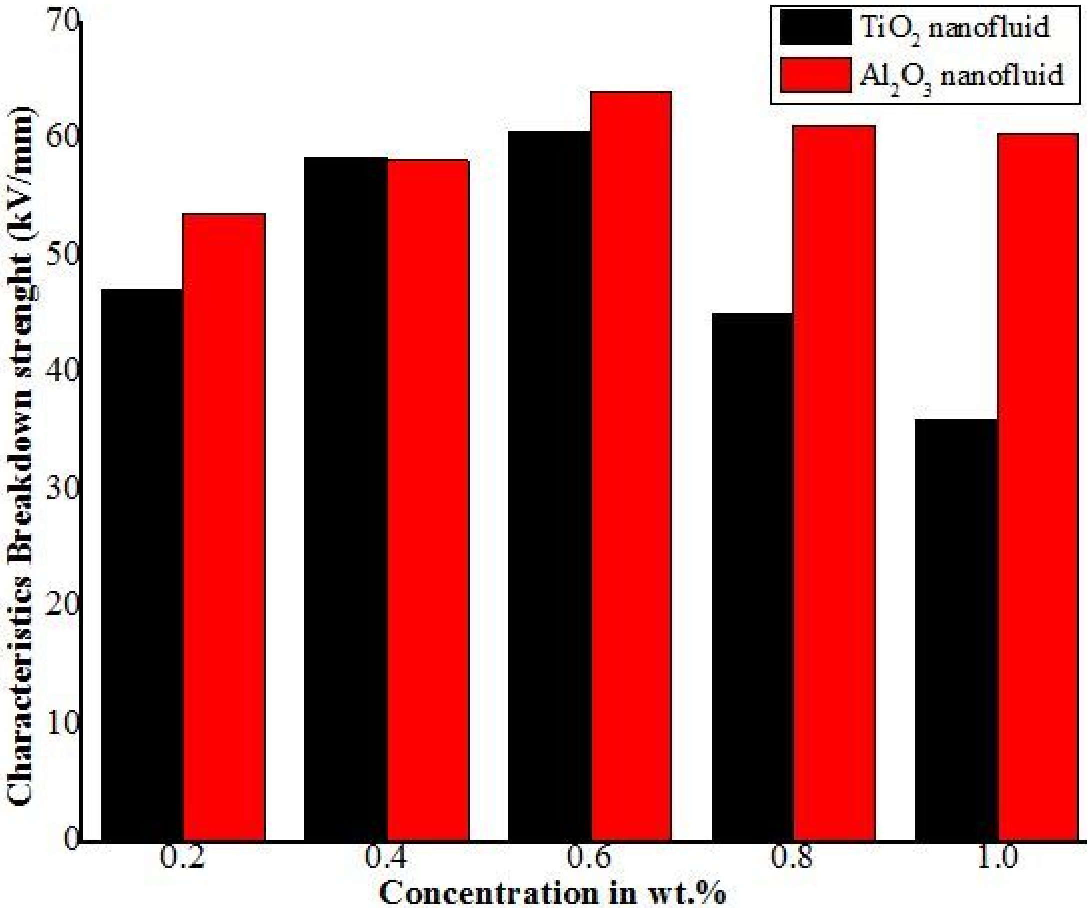

Figure 9

Characteristic breakdown strength of TiO2 and Al2O3 nanofluids