Investigative study on the AC and DC breakdown voltage of nanofluid from Jatropha–Neem oil mixture for use in oil-filled power equipment

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Received: 20 August 2021 / Accepted: 24 November 2021 / Published online: 11 January 2022
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Abstract
This paper investigated the feasibility of developing alternative insulating nanofluid from a mixture of Jatropha and Neem oils into which compositions of 0.2 to 1.0 wt% of titanium oxide nanoparticles were dispersed. FTIR, SEM–EDX and XRD analyses of titanium oxide nanoparticles were carried out. The DC and AC breakdown voltages were measured and analysed using Weibull statistical tool. In the Weibull statistical analysis, it was observed that the characteristic breakdown field strength of PJO is higher relative to PNO and has slight differences compared to the PJNO sample. With the dispersion of TiO2 nanoparticles, the characteristic breakdown strength improved as compared with the base oil. Furthermore, the developed Jatropha–Neem mixture nanofluid recorded characteristic breakdown field strength that is much higher compared to that of the mineral oil sample. The mixture of Jatropha and Neem oil nanofluid sample possessed the highest characteristic breakdown strength among prepared nanofluids which indicates that the characteristic breakdown strength of the oil samples has been improved considerably with the dispersion of TiO2 nanoparticles. The results have shown the viability of Jatropha–Neem nanofluid as insulating oil for use in oil-filled power equipment.

Keywords Dielectric · Insulator · Dielectric properties · Energy storage · Statistics/statistical methods

1 Introduction
Insulating oil is used in oil-filled power transformers for electrical insulation and cooling. It transfers heat away from power equipment at the same time; it stops arcing and corona discharge in the transformer system. More importantly, they provide a suitable way of routine examining the condition of electrical equipment over its service life [1]. The expected life span of transformers ranges from 35 to 40 years, but available transformer failure statistics have shown that the typical service life of transformer failure nowadays is 18 years, owing to insulation problems [2]. An effective functioning and lifetime of power equipment depend mainly on the quality of insulation materials. Conventional mineral oil has been used as an insulating and cooling material since the 1900s because of its good ageing property, low viscosity, availability and low cost [3]. At a particular period, the use of nanoparticles in improving the insulating properties of the mineral oil was introduced by the researchers in the year 1995. Despite the aforementioned merits, the demerits of the mineral-based insulating fluids such as its high fire risk, low biodegradability potential couple with its scarcity in the near future because the oil resources will run out and there is an increase in electric power consumptions across the globe, particularly, Nigeria [4, 5]. Also, transformers failure and leakage of their oil are toxic to the aquatic life and not friendly to the environment. This provided an impetus to scientists to focus and search for a superior alternative to mineral-based insulating fluid from renewable energy sources such as vegetable oil from a plant seed.

Vegetable oil is identified as an environmentally friendly alternative. However, it was found that they have high viscosity which reduces the easy flow of insulating oil in power equipment coupled with high dielectric loss [6, 7]. Dispersion of nanoparticles in these oils has been found to reduce the dielectric loss and improve other electrical properties such as dielectric constant and AC breakdown
Similarly, mineral-based insulating nanofluids have been reported to have attained high electrical insulation [10]. Interestingly, the enhancement reported on the part of seed-based nano-insulating oils shows that these oils can replace the mineral-based insulating nanofluid in power equipment [11]. However, many factors still make seed oil with nanoparticles unfit for proper insulation. For example, the problem associated with the instability of the nanofluid. Reports show that unsaturated fatty acids have a lower melting point and pour point relative to the saturated fatty acid. This is because crystal formation in unsaturated fatty acids is difficult due to the presence of bends and kinks introduced by the carbon–carbon double bond. Neem and Jatropha oil is selected in this work due to their high level of unsaturation as it enhances the melting and pour point which is the desired property for good insulating oil. Also, the issue associated with the suspension of nanoparticles in the insulating oil was addressed by coating the surface of the nanoparticle with oleic acid. Poor cohesion between the nanoparticles and the base fluid has been reported to occur soon after the nanoparticles were dispersed into the oil. This causes the particles to settle at the bottom of the base fluids within a short period after dispersion [11]. This paper presents the synthesis of a stable nanofluid through functionalization of the nanoparticle with the aid of oleic acid. Furthermore, the effect of the coated nanoparticle on DC and AC breakdown voltage of Jatropha–Neem nanofluid was studied.

2 Materials and method

2.1 Materials

_Jatropha curcas_– and Neem seed–based oils were procured from National Research Institute for Chemicals Technology (NARICT), Zaria, Nigeria. Citric acid, silica gel and Fuller earth, magnetic stirrer, KOH solution, oleic acid, ethanol and titanium oxide nanoparticle were used in this work.

2.2 Methods

Dijkstra and Opstal procedure was employed for purification of oils; a small quantity of crude Jatropha curcas and Neem oils was purified in a conical flask. Citric acid was used as a catalyst in the company with KOH solution. Of silica gel, 0.5 g was added to the oil at 70 °C and then agitated for 30 min at 1200 rpm. Of Fullers’ earth, 2.5 g was then added and swirled with a magnetic stirrer for 30 min at a constant temperature. The oils were then filtered with a hand filtering instrument and re-filtered in a vacuum oven at 80 °C.

A sample of purified Jatropha and Neem seed oils in equal ratios was poured into a conical flask and heated to 80 °C for 1 h. The functionalization method by [12] was adopted where 10 g of TiO_2_ nanoparticles was dispersed in 200 ml of ethanol followed by the addition of 0.5 ml of oleic acid. Nanofluid was prepared by adding 0.2 to 1.0 wt% concentration of titanium oxide (TiO_2_) nanoparticles to the oil. The sample was swirled with a magnetic stirrer at the rate of 1200 rpm for 25–30 min to disperse the nanoparticles and prevent agglomeration. Nicolet 6700 FTIR spectrometer was used to perform the Fourier transforms infrared analysis of the oleic acid–coated particles. The surface morphology of the nanoparticle was studied using SEM–EDX analysis while the crystal-lite size was determined using X-ray diffraction. AC and DC breakdown voltage measurements were performed on the samples in accordance with the guidelines of ASTM D1816 [13]. AC breakdown voltage was conducted using an automatic breakdown kit while the DC breakdown test was conducted with the test set shown in Fig. 1. (Table 1 shows the sample descriptions of the base oil and of the prepared nanofluids).

3 Results and discussion

3.1 Nanoparticle analysis

3.1.1 SEM–EDX analysis

The surface morphology and elemental composition and the SEM–EDX analysis were done on TiO_2_ nanoparticle. Figure 2a shows the micrograph image of TiO_2_ nanoparticle with an abundance of quasi-spherical shaped particles. The elemental composition of the nanoparticle in Fig. 2b showing the peak of Ti and O is evidence of the purity of the nanoparticles.
3.1.2 XRD analysis

X-ray pattern of TiO₂ nanoparticles was used to determine the average crystallite size. In Fig. 3, the diffraction peaks can be attributed to TiO₂ nanoparticles and the two intense peaks of 2θ at 25.26° and 47.84° can be attributed to the anatase phase (JCPDS file no. 21–1272) [12]. The mean crystallite size of the nanoparticles was calculated using the Debby–Scherer equation, and the average particle size of TiO₂ is 11 nm.

3.1.3 Fourier transform infrared spectroscopy

The result of pure and coated TiO₂ nanoparticles can be seen in Fig. 4a, b. At 3235 cm⁻¹, an asymmetric and symmetric stretching is observed which is related to the hydroxyl group (Ti–OH). Also, at 1636 cm⁻¹, deformation vibration of Ti–OH bending mode is observed which implies that these two observed peaks are characteristic of O–H bending modes of adsorbed water and hydroxyl groups on the TiO₂ surface. The band from 1000 to
400 cm$^{-1}$ is the fingerprint of Ti–O stretching and Ti–O–Ti bridging stretching modes. The peak at 650 cm$^{-1}$ is within the range of anatase. Titania is an indication that the titanium oxide nanoparticle used is anatase. An absorption peak of CH$_2$ at 2926 cm$^{-1}$ was observed in the spectrum of the coated TiO$_2$ which does not reflect in pure TiO$_2$ nanoparticles. The CH$_2$ peak in the coated TiO$_2$ is an indication that oleic was successfully coated on the TiO$_2$ nanoparticle. The peak at 1461 cm$^{-1}$ is a fingerprint of carboxylate which proves the combination of oleic acid and nanoparticle surfaces.

![FTIR spectra](image)

**Fig. 4** a FTIR of pure TiO$_2$ nanoparticles. b FTIR of oleic-coated TiO$_2$ nanoparticles

**Table 1** Description of samples

| Sample code | Description                |
|-------------|----------------------------|
| MO          | Mineral oil                |
| PIO         | Purified Jatropha oil      |
| PNO         | Purified Neem oil          |
| PINO        | Purified Jatropha–Neem oil |
| JNF         | Jatropha nanofluid         |
| NNF         | Neem nanofluid             |
| JNNF        | Jatropha–Neem nanofluid    |

The International Journal of Advanced Manufacturing Technology (2022) 119:4375–4383
3.2 Nanofluid sample analysis

3.2.1 Basic properties oil samples

The basic properties of the mineral oil (MO), purified Jatropha oil (PJO), purified Neem oil (PNO), purified Jatropha and Neem mixture (PJNO), Jatropha nanofluid (JNF), Neem nanofluid (NNF) and the mixture of Jatropha and Neem oil nanofluid (JNNF) at 1 wt% and power frequency 60 Hz are shown in Table 2.

From Table 2, the loading of TiO$_2$ nanoparticle leads to an increase in the relative permittivity of the base fluid. This can be attributed to an increase in the polarization rate of the mixture which is caused by the TiO$_2$ nanoparticle. Dielectric liquid with high permittivity is desired when it comes to insulation in high voltage equipment. In this regard, the Jatropha–Neem nanofluid with the highest permittivity at 1 wt% can be considered as an insulating liquid. Also, a decrease in the dielectric loss was observed after the loading of the nanoparticle and this can be attributed to nanoparticle obstructing the charge transport in the base fluid which, consequently, decreases the conductivity. Equation 1 shows the relationship between dielectric loss and conductivity. The dielectric loss of JNNF among others appears to be the best, and this value obtained is better than the value obtained by Oparanti et al. [12, 13] where they obtained the dielectric loss of purified palm kernel to be 0.00631.

\[ \sigma = \omega \epsilon'' \] (1)

The viscosity of the purified oil was found to be slightly higher than that of mineral oil but still within the range of the recommended value by IEC 60,296 and ASTM D3487. The addition of the nanoparticle to the base oil slightly reduces the viscosity at 1 wt%. The decrease in viscosity of the base fluid after the loading of the nanoparticle can be attributed to the reduction in the frictional force that exists between the molecules of the oil. The low viscosity value in high voltage insulation is the desired one as it helps in proper cooling and prevents localized heating and hotspot formation.

Furthermore, the flash point of the purified Jatropha oil, Neem oil and the mixture of the oils is 75%, 72.8% and 70% greater than the flash point of mineral oil, respectively. The loading of the nanoparticle at 1 wt% increases the flash point of the base fluid by preventing molecular dissociation in the oil through absorption of heat from electrical stress by the nanoparticles. The flash point of JNF, NNF and JNNF is 82.8%, 77.1% and 86% greater than that of conventional mineral oil. The increase in this flash point is similar to the report made by Oparanti et al. [12] where they reported an increase in the flash point of methyl ester of palm kernel oil through the addition of TiO$_2$ nanoparticle. The high flash point value of Jatropha–Neem oil nanofluid at 260 °C is an indication of less flammability which prevents fire outbreaks during fault condition.

3.2.2 High voltage analysis

The high voltage DC properties of the samples with 1 wt% nanoparticle were studied in a hemisphere–hemisphere electrode test cell using a high voltage test setup with a 35-kV DC source. HVDC was applied through the samples to determine the leakage current. The voltage was supplied by increasing the voltage by 0.5 kV at 0.5 steps to record the leakage current and determine the voltage at which breakdown occurs. This was performed on MO, PJO, PNO, PJNO, JNF, NNF and JNNF. The average HVDC leakage current flowing through the samples was calculated using Ohm’s law through the measured output voltage and the resistance of the measuring resistor. The plot of the measured HVDC leakage current against the applied voltage for MO, PJO, PNO and PJNO samples is displayed in Fig. 5. The characteristic curves for MO, PJO, PNO and PJNO oil show that the DC leakage current increases almost linearly with the applied voltage. This is similar to the report made by Oparanti et al. and Makmud et al. [12, 14]. For all the oil samples, the HVDC leakage current is ionic and increases linearly with the applied voltage. It is imperative to notice that the samples PJO, PNO and PJNO without TiO$_2$ nanoparticles were observed to have an HVDC leakage current that is comparable with the mineral oil sample (MO) as illustrated in Fig. 5. The lower the volume resistivity, the higher the leakage current and the more the conductive the material is, but good oil for oil-filled power equipment; the resistivity should be high to prevent any form of conduction in the system. Insulating oil with lower resistivity indicates the presence of moisture and conductive contaminating agents which could lead to thermal breakdown.

In the case of pure oil samples, the characteristic curve depicts that the current increases slightly with applied voltage. Figure 5 displays a linear growth as the applied voltage

![Table 2 Basic properties of purified oil and 1 wt% TiO2 nanofluid (27 °C)](image)

**Table 2** Basic properties of purified oil and 1 wt% TiO$_2$ nanofluid (27 °C)

| Sample | Dielectric constant at 60 Hz | Dielectric loss at 60 Hz | Viscosity(mPa s) at 40 °C | Flash point (°C) |
|--------|----------------------------|--------------------------|--------------------------|-----------------|
| MO     | 2.21                       | 0.00225                  | 9.82                     | 140             |
| PJO    | 3.58                       | 0.0551                   | 11.07                    | 245             |
| PNO    | 3.44                       | 0.0244                   | 11.10                    | 242             |
| PJNO   | 3.63                       | 0.02365                  | 11.41                    | 238             |
| JNF    | 7.26                       | 0.002151                 | 10.01                    | 256             |
| NNF    | 6.78                       | 0.00208                  | 9.930                    | 248             |
| JNNF   | 8.36                       | 0.001862                 | 9.874                    | 261             |
Increases. The TiO$_2$ nanoparticles in the oil act as electron traps by slowing down the streamers speed which contributes to improving dielectric strength. The breakdown voltages of the prepared nanofluids were observed to be higher when compared with the purified oil samples. The breakdown voltage of JNF and NNF was recorded to be 25 kV and 24 kV, respectively. The nanofluid from the mixture of the two seed oils produced a composite material with a breakdown voltage of 26 kV at 1 wt% loading. This implies that the DC electrical strength of the oil-based nanofluids is better than that of based oil samples without the addition of TiO$_2$ nanoparticles.

Meanwhile, the recorded leakage current shows a nearly ohmic relationship. The leakage current through the nanofluids was observed to be higher than that of the purified oil samples, an indication that the nanofluids have slightly lower DC resistance. This revealed an indication that DC breakdown does not rely completely on the resistance of the material. Charge injection from the electrodes may have played a greater role in the breakdown of the samples. The obtained result indicates that the dispersion of nanoparticles enhanced breakdown voltage; this finding could be explained by the fact that the polarized TiO$_2$ nanoparticles can act as electron traps to catch the free electrons released from oil molecules under a high electric field and that would otherwise cause a breakdown. It could also be related to the higher chance of electron scattering in nanofluids due to the high specific surface area of nanoparticles. Therefore, adding TiO$_2$ nanoparticles to base oil have improved breakdown voltage at the optimum concentration of 0.6 wt% loading. This is in close agreement with Given et al. and Khedkar et al. results [15, 16]. The nanofluid from the mixture of Jatropha and Neem appeared to have high breakdown strength, and this signifies that nanofluid samples prepared can be suitable for electrical insulation. This result complies with a fixed standard and conforms with that obtained by Mehta et al. [2].

### 3.2.3 Weibull analysis

The Weibull distribution plots were used instead of normal distribution, though normal distribution is a very important

| Samples | Number of readings (N) | Characteristic breakdown strength (kV mm$^{-1}$) | 95% confidence bound for $\alpha$ (kV mm$^{-1}$) | Shape parameter $\beta$ (kV mm$^{-1}$) | 95% confidence bound for $\beta$ (kV mm$^{-1}$) | Correlation coefficient |
|---------|-----------------------|-------------------------------------------------|-----------------------------------------------|---------------------------------|-----------------------------------------------|------------------------|
| MO      | 6                     | 36.8                                            | 37.03–43.17                                   | 12.80                           | 7.29–30.71                                    | 0.855                  |
| PJO     | 6                     | 28.7                                            | 29.10–40.10                                   | 6.13                            | 3.49–14.70                                    | 0.933                  |
| PNO     | 6                     | 15.1                                            | 15.53–29.17                                   | 3.12                            | 1.77–7.48                                     | 0.940                  |
| PJNO    | 6                     | 15.8                                            | 15.95–19.07                                   | 11.00                           | 6.26–26.38                                    | 0.959                  |
| NNF     | 6                     | 18.5                                            | 18.65–23.41                                   | 8.63                            | 4.91–20.71                                    | 0.932                  |
| JNF     | 6                     | 25.7                                            | 25.93–31.12                                   | 10.77                           | 6.13–25.84                                    | 0.937                  |
| JNNF    | 6                     | 35.6                                            | 35.64–37.35                                   | 41.81                           | 23.81–100.31                                  | 0.981                  |
and well-known probability distribution for dealing with problems in scientific data. However, there are numerous situations when the assumption of normality is not validated by the data. Weibull provides better goodness of fits than the generalization of the normal distribution. Weibull parameters of the breakdown strength data for purified Jatropha oil (PJO), purified Neem oil (PNO), purified Jatropha–Neem oil mixture (PJNO), Jatropha nanofluid (JNF), Neem nanofluid (NNF), Jatropha–Neem nanofluid (JNNF) and mineral oil (MO) samples were extracted from the plots. Table 3 shows the Weibull parameters of AC breakdown strength of mineral oil (MO), Jatropha–Neem oil (JN) and Jatropha–Neem nanofluid (JNNF) samples. Mineral oil has the highest breakdown field strength followed closely by Jatropha–Neem nanofluid. Both the characteristic breakdown field strength and the shape parameter of Jatropha–Neem oil improved considerably with the addition of TiO$_2$ nanoparticles. The breakdown field of Jatropha–Neem nanofluid (JNNF) has narrow distribution as indicated by the values for the fitted shape parameter, β as seen in Figs. 6, 7 and 8. This observation is in close agreement with the previously reported result by Henry et al. [17].

Fig. 6 Weibull plot of AC breakdown field data for MO

Fig. 7 Weibull plots of AC breakdown field data for samples PJO, PNO and PJNO
The characteristics breakdown strength of oil samples for the selected probability of failures can be seen in Table 4. There is a situation where failure occurs at low voltage; therefore, breakdown voltage at the lowest probability (1%) for each sample was also considered. It was observed that the breakdown strength of the prepared JNNF at the lowest probability is better than all the prepared oil including mineral oil. Therefore, the obtained result at 1% probability demonstrates the high operating reliability of the JNNF insulating fluid.

### Table 4 Weibull probability of the AC breakdown voltage for all oil samples at 1%

| Weibull probability (%) | MO  | PJO | PNO | PJNO | JNF  | NNF  | JNNF |
|-------------------------|-----|-----|-----|------|------|------|------|
| 1                      | 25.67 | 13.54 | 3.45 | 10.42 | 16.78 | 10.83 | 31.86 |
| 5                      | 29.16 | 17.67 | 5.82 | 12.03 | 19.52 | 13.09 | 33.12 |
| 10                     | 30.84 | 19.87 | 7.33 | 12.90 | 20.87 | 14.22 | 33.70 |
| 30                     | 33.93 | 24.24 | 10.85 | 14.41 | 23.37 | 16.38 | 34.69 |
| 63.2                   | 36.77 | 28.68 | 15.10 | 15.83 | 25.72 | 18.46 | 35.56 |

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### 4 Conclusion

In this work, Jatropha and Neem oils were purified and the titanium oxide nanoparticles were functionalized with oleic acid. The stability of the prepared nanofluid was enhanced after the functionalization of the nanoparticle due to the improved interfacial zone of the nanofluid as a solid–liquid suspension. The dielectric constant values of the PJO, PNO, PJNO JNF, NNF and JNNF were found to have increased linearly with an increase in the concentration of titanium oxide nanoparticles (TiO₂). The dielectric loss of the oil reduces after the loading of the nanoparticle, and the loss of the mixture of the oil-containing TiO₂ nanofluid was obtained to be 0.001862 which is lower than the dielectric loss of the mineral insulating oil, 0.00225. The results also show that characteristic values of the purified oils samples and their mixture have lower values than the synthesized nanofluids. A sample of JNNF recorded the highest characteristic value among all the samples prepared. As such, the developed nanofluid with the precise amount mixture from Jatropha and Neem oils could be a viable insulation fluid for use in oil-filled power equipment. This research in some ways will also enhance the cultivation of these agricultural products and, consequently, reduce the rate of unemployment in society. Further investigation should be done on this oil combination. The mixture of the transesterified oil should be studied.

### Funding

This work was supported by Nigeria’s Tertiary Education Trust Fund (TETFund) National Research Fund (NRF) Research Grant 2019. /DR&D/CE/NRF/UNI/ZARIA/STI/55/VOL.1

### Declarations

**Ethics approval**  Not applicable.

**Consent to participate**  Not applicable.
Consent for publication  Not applicable.

Conflict of interest  The authors declare no competing interests.

References

1. Wanikhalid S, Ankush R, Mir Irfan U (2018) Friction and wear characteristics of vegetable oils using nanoparticles for sustainable lubrication.

2. Mehta DM, Kundu PA, Chowdhury A, Lakhaiani VK, Jhala AS (2016) A review on critical evaluation of natural ester vis-à-vis mineral oil insulating liquid for use in transformers: part 1. IEEE Trans Dielectr Electr Insul 23:873–880

3. Issouf F (2013) 50 years in the development of insulating liquids. Article in IEEE Electr. Insul. Mag 9(5):13–16

4. Rouabeh J, M’barki L, Hammami A, Jallouli I, Driss A (2019) Studies of different types of insulating oils and their mixtures as an alternatives to mineral oil for cooling power transformers. Heliyon 5(3):e01159. https://doi.org/10.1016/j.heliyon.2019

5. Mohsen Z (2011) Measurement of ion mobility in dielectric liquids, master of science thesis in electric power engineering, department of materials and manufacturing technology division of high voltage engineering, Chalmers University of Technology Goteborg, Sweden

6. Abdelmalik AA (2015) Analysis of thermally aged insulation paper in a natural-ester-based dielectric fluid. IEEE Trans Dielectr Electr Insult 22:2408–2414

7. Suwarno A, Rajab A, Salaeman A, Sudirhan S (2018) Comparison of dielectric properties of palm oil with mineral and synthetic type insulating liquid under temperature variation. ITB J. Eng. Sci 43:191–208

8. Oparanti SO, Khaleed AA, Abdelmalik AA, Chalashkanov NM (2020) Dielectric characterization of palm kernel oil ester-based insulating nanofluid. IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) 2020:211–214. https://doi.org/10.1109/CEIDP.2020.9437477

9. Mansour DE, Atyi EG, Khattab RM, Azmy AM (2012) Effect of titanium nanoparticles on the transformer oil-based Nano fluids. Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp 295–298

10. Sanchez-Dominguez M, Rodriguez-Abreu C (2016) Nano colloids: a meeting point for scientists and technologists

11. Sayanta M, Paria S (2013) Preparation and stability of nanofluids: a review. J Mech Civ Eng 9(2):63–69

12. Oparanti SO, Khaleed AA, Abdelmalik AA (2021) Nano fluid from palm kernel oil for high voltage insulation. Mater Chem Phys 259:123–961

13. Oparanti SO, Khaleed AA, Abdelmalik AA (2021) AC breakdown analysis of synthesized nano fluids for oil-filled transformer insulation. Int J Adv Manuf Technol 117:1395–1403. https://doi.org/10.1007/s00170-021-07631-0

14. Makmud MZH, Illias HA, Chee CY, Sarjadi MS (2018) Influence of conductive and semi-conductive nanoparticles on the dielectric response of natural ester-based nanofluid Insulation. Energies 11(2):333

15. Given MJ, Wilson MP, McGlome P, Timoshkin IV, Wang T, MacGregor SJ (2011) The influence of magnetite nanoparticles on the behaviour of insulating oils for pulse power applications. IEEE, Conf Electr Insul Dielectr Phenomena, pp 40–43

16. Khedkar RS, Shrivastava N, Sonawares S, Wasewar K, L. (2016) Experimental investigation and theoretical determination of thermal conduction and viscosity of titanium oxide ethylene glycol nanofluid. Int Commun Heat Mass Transfer 73:54–61

17. Henry BH, Abderranhanme B, Rudy S, Setijo B (2017) Statistical analysis of AC and DC breakdown voltage of JMEO (jatropha methyl ester oil), mineral oil and their mixtures. 19th IEEE International Conference on Dielectric Liquids(ICDL), UK

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