# Impact of Iron, Silicon and Boron Nanoparticles on the AC Breakdown voltage of Rice Bran Oil in the presence of CTAB

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***Abstract*— The power and energy sector is embracing modern technology across various scientific fields to enhance efficiency, particularly with the integration of distributed generation and smart grids. A crucial element in power transmission and distribution is the Transformer, which is commonly filled with oil and used in both high voltage transmission and low voltage distribution. To improve the operational efficiency of these large machines, researchers are conducting studies to develop insulating oils with high dielectric strength. This research aims to enhance the dielectric properties of natural oil-based insulating fluids by incorporating suitable nanoparticles. Edible oil such as rice bran oil has been selected for this purpose. Nanoparticles such as iron ($Fe_3O_4$), silicon ($SiO_2$) and Boron (h-BN) have been chosen as additives. The breakdown Voltage is compared among different samples. The impact of cetyltrimethylammonium bromide (CTAB) as a surfactant was also investigated. The results obtained demonstrate the potential to create natural vegetable-based oils with nanomaterial additives, such as white graphene, which possess superior qualities compared to traditional mineral-based transformer oils. The concentration of each nanoparticle used is 0.01, 0.025, and 0.05 g/L. Two-step processes involving sonication and drying are employed to disperse the nanoparticles. The AC breakdown voltage is assessed following the guidelines of the IEC 60156 standard. The findings indicate that the addition of 0.025g/L of iron nanofluid significantly enhances the AC breakdown voltage of rice bran oil, while boron nanofluid demonstrates a moderate effect, with the highest improvement observed at a concentration of 0.01g/L. In contrast, the presence of silicon nanofluid results in the lowest breakdown voltage among the three mentioned nanoparticles. The inclusion of CTAB in RBO nanofluids reduces the AC breakdown voltage. Iron, silicon, and boron show potential for future transformer applications.***

***Keywords*— *AC breakdown voltage, boron, CTAB, insulation, iron, nanofluids, nanoparticles, normal distribution, rice bran oil, silicon.***

## I. INTRODUCTION

Power transformer is an important equipment in the power and distribution networks. For a reliable supply of electricity to utilities, it is crucial to guarantee that the power transformer is operating at its peak efficiency and must be protected from breakdown [1]. The power transformer consists of several components, including the insulation system. The insulation materials of the transformer include solid materials (paper) and liquid materials (oil) [2].

Mineral-based oils have been traditionally used as insulating fluids in transformers. However, there are several issues and challenges associated with their use in transformer applications. First is the environmental impact. Mineral oils are derived from non-renewable fossil fuel sources. Their extraction and processing contribute to environmental pollution, including greenhouse gas emissions. Additionally, the disposal of used mineral oil poses environmental risks if not handled properly. Next is the fire hazard issue. Mineral oils have a relatively low flashpoint, which means they can ignite and burn easily. In transformer applications, where high temperatures and electrical currents are present, the risk of fire and explosion is a concern. The most important concern is limited temperature stability. Mineral oils have a limited temperature range in which they can effectively operate. High operating temperatures can lead to degradation of the oil, resulting in reduced insulation performance and shorter lifespan of the transformer. Cooling systems or additional measures may be required to control temperature and prevent overheating.

To address these challenges, alternative insulation fluids are being explored. Vegetable-based oils and other environmentally friendly options are being considered as potential replacements for mineral oils. These alternatives offer improved fire safety, higher temperature stability, and better environmental sustainability [3].

Vegetable oil is an alternative green option insulating oil for transformer application. It gained attention due to several benefits which includes biodegradability, sustainability, high flash, and fire point, improved thermal stability and lower toxicity [4]. In Asian nations, Rice Bran Oil (RBO) is widely utilised. The outer layer of the brown rice kernel, which makes up 6-8% of the paddy rice, is where RBO is formed as a by-product of the rice milling process. It is commonly utilised for many other things, such as cooking, gasoline, and biodiesel. In 2022, M.H.A. Hamid investigated RBO's potential as a substitute for transformer oil. The initial investigation revealed that the performance of RBO is comparable to palm oil (PO) and mineral oil (MO) for the AC breakdown voltage under 2.5, 3.5, and 5, 10 mm gap distances. According to the findings, RBO has better lower dielectric dissipation factor, which will improve the ability of the insulating oil [5].

However, the vegetable oil especially rice bran oil does not possess the necessary properties to meet the existing standards required for insulating oil in transformers. Therefore, a comprehensive study has been conducted using different samples obtained by incorporating base oil (rice bran oil) with various nanoparticles, aiming to improve their properties [3,6].

Numerous studies have been done on the effects of nanoparticles on the electrical properties of dielectric materials all over the world over the past 20 years on their ability to record the initiation voltage of partial discharges and to slow the propagation of electrical discharges, trees in polymers, and streamers in liquids, which can cause breakdown [7]. Nanofluid, a suspension of nanoparticles (at least one dimension less than 100 nm) in a base fluid with better thermal, rheological, and water sorption characteristics, enhances the performance of many applications.

Nanoparticles could enhance the breakdown voltage, flashpoint, DC resistivity, and thermal conductivity of insulation fluids [8]-[10]. The improved characteristics and functionality of nanofluids depend on factors such as particle size, consistency, stable suspensions, concentrations, and production methods [11]. The technique involves dispersing the nanoparticles in a base fluid after mixing them with a surfactant. The surfactant plays a crucial role in sustaining the stability and suspension of the nanoparticles in the base fluid, preventing their agglomeration. This increased particle-particle contact facilitated by the surfactant leads to a more stable dispersion of nanofluids, resulting in a longer-lasting effect [12,13]. Nanoparticles often aggregate to form clusters that are larger than the sum of their individual elements. This agglomeration accelerates sedimentation, leading to a loss of thermophysical characteristics such as viscosity, thermal conductivity, thermal performance, and increased pressure drop and can cause detrimental to the lifespan of the transformer before breakdown occurs [14]. To address this stability issues, nanofluid has attracted a lot of interest in the engineering community with one of the ways is by adding surfactant. Surfactant are known to decrease the agglomeration of nanoparticle and improve the dispersion of nanoparticle [15]. Surfactants have a wide range of uses in research and business, from fundamental procedures like the recovery and purification of raw materials in the mining and petroleum industries to improving the quality of finished goods like paints, cosmetics, medications, and food [16]. The surface tension between water and lipids is said to be reduced by adding surfactant to the nanofluid [17] and prohibit the nanofluid from aggregate [18].

Therefore, this study introduce surfactant, Cethyl trimethyl ammonium bromide (CTAB) into the nanofluids sample to see its impact on the stability of the nanoparticles. CTAB is commonly used in various scientific and industrial applications, including the synthesis and stabilization of nanoparticles, micelle formation, DNA extraction, and as a surfactant in the preparation of emulsions and colloidal systems Until now, there are still limited research for iron, silicon, and boron nanoparticles for rice bran oil with the presence of CTAB in the literature.

## II. PREPARATION OF NANOFLUIDS

Generally, there are two primary techniques to prepare nanofluids, which are the one-step and two-step process. In the one-step process, nanoparticles are synthesized in the base fluid by chemical method, while in two-step process firstly prepares nanoparticles in a form of powders and then dispersed in base fluid. However, the two-step method is extensively used by most researchers due to the production method being found straightforward and much cheaper. Hence, a two-step preparation method is carried out in preparing nanofluids in this research. Fig. 1 shows the two-step preparation process of nanofluids.

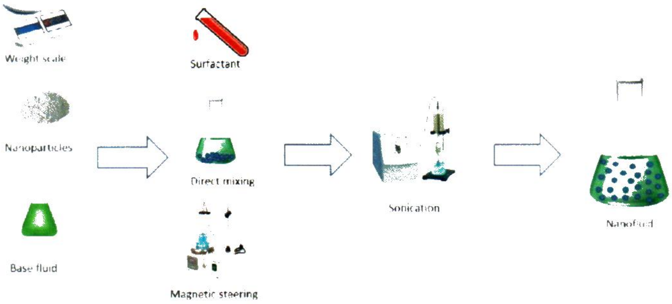

Fig. 1: Preparation of Nanofluid using Two-step Method

For this study, there were three different nanoparticle concentrations used: 0.001 g/L, 0.025 g/L, and 0.05 g/L. The oil underwent three rounds of filtration using a membrane filter with a pore size of 0.2 µm to remove any particles that can affect the result. Next, the oil was dried for 48 hours at 85°C in a VO200 Memmert vacuum oven to remove any trapped moisture, as moisture can adversely affect the performance of the insulating oil in the nanofluid.

The nanoparticles were then accurately weighed using an analytical weighing machine and mixed with the base oil using a magnetic stirrer. In the case of nanofluids with a surfactant, the surfactant was added to the base oil prior to the introduction of the nanoparticles and stirred in a similar manner. The concentration of the surfactant used was 50% of the concentration value of the nanoparticles, which translated to 0.005 g/L, 0.013 g/L, and 0.024 g/L. The choice of surfactant concentration was based on a report by Mohamad, N.A. in 2017, which suggested that the optimal surfactant concentration was found to be 50% of the volume concentration of the nanoparticles [15].

The sonication process was carried out at a 30-amplitude setting for 15 minutes, with a pulse on and off time of 1 second and 5 seconds, respectively. After the sonication procedure, the oil was allowed to rest at room temperature for a day before proceeding with the AC breakdown voltage measurement. A total of 18 samples were recorded for analysis, considering each nanoparticle type, concentration, and the presence of CTAB. The details of nanoparticles are shown in Table 1, and while Table II depicts the basic properties of CTAB.

TABLE I. BASIC PROPERTIES OF IRON, SILICON AND BORON NANOPARTICLES

| Properties | Iron | Silicon | Boron |
|---|---|---|---|
| Size (nm) | 1-100 | 1-100 | 20-80 |
| Appearance color | Black | Black | Black |
| Density (g/cm$^3$) | 7.87 | 2.33 | 2.34 |
| Relative permittivity | ~1 | ~11.7-13 | ~4.7-7 |
| Electrical conductivity (S/m) | $1.04x10^{7}$ | $2.3x10^{12}$ | ~10^15 |
| Thermal conductivity (W/m.K) | 80.2 | 148 | 27 |

TABLE II. BASIC PROPERTIES OF CETYL TRIMETHYL AMMONIUM BROMIDE (CTAB

| Properties | CTAB |
|---|---|
| Description | Cationic |
| Form | Solid |
| Colour | White |
| Melting point (°C) | 284 – 251 |
| Flash point (°C) | 244 |
| Flammability | Not flammable |
| Description | Cationic |
| Form | Solid |

## III. AC BREAKDOWN VOLTAGE TEST

The AC breakdown voltage test was conducted in accordance with the IEC 60156 standard [19] using the Baur DTA 100 C equipment. The standard recommends employing a distinct glass test vessel for each unique oil sample, with the vessel undergoing a minimum of three rinses to eliminate any potential contamination during testing. To prevent the entrapment of air in the test vessel, it is crucial to swiftly pour the oil samples, minimizing turbulence.

The standard requires the use of mushroom-shaped electrodes with a spacing of 2.5 mm, as depicted in Fig.2. To avoid the formation of air bubbles, a 400 ml capacity test cell was carefully placed inside the test vessel. During the test, an AC voltage with a frequency of 50 Hz and a rate of increase of 2 kV/s was applied to the nanofluid until breakdown occurred. To ensure equal distribution of the breakdown process between the two electrodes, a magnetic stirrer was utilized. Between two breakdown events, there was a 5-minute resting period. The parameters specified in the IEC 60156 standard can be found in Table III.

Fig. 2 Mushroom shaped electrodes with 2.5mm

TABLE III. IEC 60156 STANDARD PARAMETER

| Test Standard | IEC 60156 |
|---|---|
| Electrode gap distance | 2.5 mm |
| Type of electrode | Mushroom or Spherical |
| Stirring using impeller | Optional |
| Stirring using magnetic bead | Optional |
| Number of breakdown sequence | 6 |
| Test vessel limitation | 0.35-0.6 litres |

## IV. RESULTS AND DISCUSSION

The result for pure RBO AC breakdown voltage is 61.12kV with the standard deviant 13.9kV at room temperature. This will be the base result for comparison in this study. Fig. 3 shows the data of breakdown voltage for RBO nanofluids without the presence of CTAB. Based on the data presented in Figure, it can be concluded that the introduction of iron nanoparticles ($Fe_3O_4$) without CTAB has a positive effect on the AC breakdown voltage of RBO. The AC breakdown voltage shows a linear increase from 70.65 kV to 90.09 kV as the concentration of iron nanoparticles increases from 0.01 g/L to 0.025 g/L. However, at a higher concentration of 0.05 g/L, the breakdown voltage decreases slightly to 73 kV, which is still higher than the breakdown voltage at 0.01 g/L.

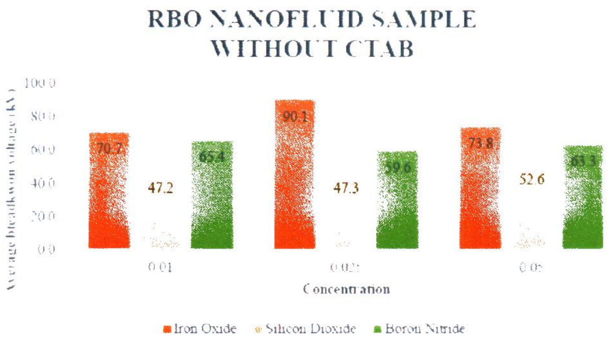

Fig. 3 RBO Nanofluids Sample without CTAB

For silicon nanoparticles ($SiO_2$), the AC breakdown voltage for all concentrations is lower than that of pure RBO. Specifically, the breakdown voltage for RBO with silicon nanoparticles is 47.23 kV for a concentration of 0.01 g/L. As the concentration increases, the breakdown voltage shows a linear increase to 47.325 kV for 0.025 g/L and further increases to 52.56 kV for a concentration of 0.05 g/L.

In the case of RBO with boron nanoparticles (BN), the AC breakdown voltage shows comparable results to pure RBO. The AC breakdown voltage values for RBO with boron nanoparticles are 65.4 kV, 59.55 kV, and 63.25 kV for concentrations of 0.01 g/L, 0.025 g/L, and 0.05 g/L, respectively. Specifically, the breakdown voltage slightly increases to 65.4 kV for a concentration of 0.01 g/L, and then decreases to 59.55 kV for both 0.025 g/L and 0.05 g/L concentrations.

Due to the presence of trapped electrons brought on by the nanoparticles, which can reduce the mobility of the free moving electrons, the AC breakdown voltage of the three nanofluid without CTAB displays a high increment for iron oxide nanoparticles. This is due to the rate of collision decreasing and greater voltage is needed to produce an electron avalanche before breakdown takes place.

CTAB (Cetyltrimethylammonium bromide) is introduced in the nanofluid as a surfactant or dispersant. Its purpose is to improve the stability and dispersion of the nanoparticles in the base fluid. CTAB molecules have both hydrophilic (water-loving) and hydrophobic (water-repelling) properties. When added to the nanofluid, CTAB molecules surround the nanoparticles, forming a protective layer around them. The introduction of CTAB helps to prevent the aggregation or clumping of nanoparticles, which can lead to sedimentation and loss of desired properties in the nanofluid.

By forming a stable dispersion, CTAB allows for a more uniform distribution of nanoparticles throughout the base fluid, enhancing their overall performance and effectiveness. Furthermore, CTAB can also enhance the interaction between nanoparticles and the base fluid, improving the compatibility and integration of the nanofluid into the system.

As seen in Fig. 4, the introduction of CTAB to RBO nanofluids decreases the AC breakdown voltage of the samples. At 0.01g/L, the RBO with $Fe_3O_4$ nanoparticle reduced the AC breakdown to 56.18 kV. For 0.025g/L, the AC breakdown voltage drops as much as 28% to 64.79 kV as compared to RBO with $Fe_3O_4$ nanoparticle with CTAB. A similar percentage drop was also found for ratio of 0.05g/L Fe3O4 nanoparticle.

For $SiO_2$ nanoparticles, the addition of CTAB in the RBO nanofluid has a varying effect on the AC breakdown voltage. Generally, the presence of CTAB tends to decrease the AC breakdown voltage of RBO nanofluid, except for a concentration of 0.05 g/L, which shows a slight improvement compared to RBO nanofluid without CTAB.

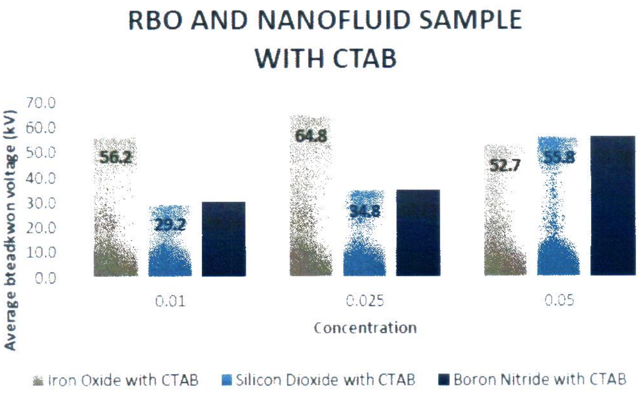

Fig.4 RBO Nanofluids sample with CTAB

Specifically, for concentrations of 0.01 g/L, 0.025 g/L, and 0.05 g/L, the AC breakdown voltages are 29.94 kV, 34.77 kV, and 55.88 kV, respectively, when CTAB is added to the BN nanoparticle based RBO nanofluid. These values are lower than the AC breakdown voltage of RBO base oil. However, it is worth noting that at a concentration of 0.05 g/L, the AC breakdown voltage with CTAB increases compared to the same concentration without CTAB, although it remains lower than the AC breakdown voltage of RBO base oil. The AC breakdown shows tremendous drop for 0.01g/L and 0.025g/L ratios as compared to the RBO with BN nanoparticles without CTAB. The percentage difference is around 40-50%.

The CTAB component decreases the nanoparticles capacity as a dielectric material. CTAB in the three nanofluids behaves as foreign substances, increasing the rate at which electrons collide elastically. The electrons will quickly multiply because of this. It becomes easier for electrical genesis as the number of electrons rises. Consequently, only little voltage is required for the voltage to travel between one electrode and another. The high viscosities of RBO may also contribute to the suspension of nanoparticles, which would therefore prevent CTAB from having any discernible beneficial effect on AC breakdown voltages.

In transformer manufacturing, designers need to consider the minimum withstand voltage level of the insulating oil rather than the average breakdown voltage. To interpret the probability distribution of breakdown failure, the commonly used statistical analysis method is the normal distribution. Therefore, the focus of this paper is on determining both the average breakdown voltage and the lowest breakdown voltage using normal distribution. The minimum with stand voltage according to standard is the probability of breakdown failure at 1% probability. This can be obtained using the AC breakdown voltage and its cumulative distribution.

Fig.5 and Fig.6 illustrate the quantile-quantile plots for the normal distribution of the AC breakdown voltage for RBO with different amounts of concentrations and different nanoparticles with and without CTAB. It facilitates the comparison and distribution conformity of the experimental values with the reference line. Based on the graph, the accuracy of RBO based nanofluids agrees with the reference line.

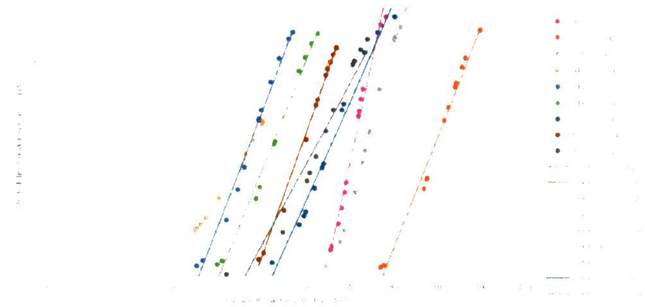

Fig.5. Scattered data from breakdown voltage of nanoparticles without CTAB

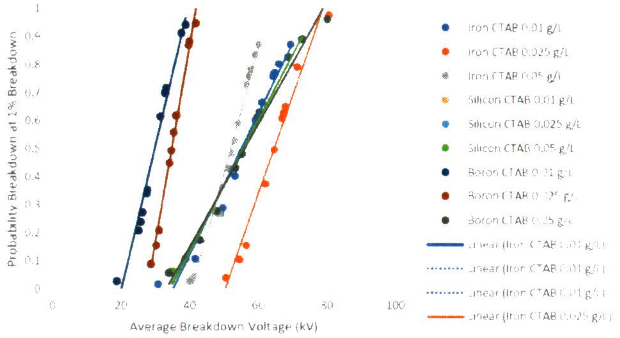

Fig.6. Scattered data from breakdown voltage of nanoparticles CTAB

Table IV shows the 1% failure breakdown voltage for RBO with all nanoparticles without CTAB. Based on the table, only silicon with ratio of 0.01g/L failed to pass the standard minimum AC breakdown voltage for liquid insulation to be used in the transformer which is set to be minimum 30 kV.

TABLE IV. AC BREAKDOWN VOLTAGE OF RBO AT 1% PROBABILITY AT DIFFERENT CONCENTRATION WITHOUT CTAB

| BREAKDOWN VOLTAGE AT 1% PROBABILITY (kV) | | |
|---|---|---|
| NANOPARTICLE | CONCENTRATION (g/L) | WITHOUT CTAB (kV) |
| IRON<br>$Fe_3O_4$ | 0.01 | 64.27 |
| | 0.025 | 78.03 |
| | 0.05 | 65.82 |
| SILICON<br>$SiO_2$ | 0.01 | 25 |
| | 0.025 | 35.31 |
| | 0.05 | 41.05 |
| BORON<br>BN | 0.01 | 52.33 |
| | 0.025 | 48.62 |
| | 0.05 | 47.29 |

The RBO with 0.025g/L shows the highest breakdown voltage with 78.03kV which shows promising result for transformer application.

TABLE V shows the 1% failure breakdown voltage for RBO with all nanoparticles with CTAB. As seen in TABLE V, adding iron to nanofluids with CTAB modestly increases AC breakdown voltage at 1% probability for RBO. After the introduction of silicon, RBO experienced clear reduction of AC breakdown voltage at 1% probability either without or with CTAB. With the introduction of boron, a slight reduction of AC breakdown voltage at 1% probability is observed with CTAB.

TABLE V. AC BREAKDOWN VOLTAGE OF RBO AT 1% PROBABILITY AT DIFFERENT CONCENTRATION WITH CTAB

| BREAKDOWN VOLTAGE AT 1% PROBABILITY (kV) | | |
|---|---|---|
| NANOPARTICLE | CONCENTRATION (g/L) | WITH CTAB (kV) |
| IRON<br>$Fe_3O_4$ | 0.01 | 35.7 |
| | 0.025 | 51.09 |
| | 0.05 | 41.9 |
| SILICON<br>$SiO_2$ | 0.01 | 20.5 |
| | 0.025 | 28.1 |
| | 0.05 | 36.48 |
| BORON<br>BN | 0.01 | 20.5 |
| | 0.025 | 28.1 |
| | 0.05 | 35.48 |

The normal distribution plot for nanofluid with CTAB is shown in TABLE V for all concentrations. For $Fe_3O_4$ nanoparticles, the lowest breakdown voltages at 1% breakdown level were 35.7 kV for 0.01g/L, 51.09 kV for 0.025g/L, and 41.9 kV for 0.05g/L. The results for $SiO_2$ were 20.5 kV, 28.1 kV, and 36.48 kV for concentrations of 0.01 g/L, 0.025 g/L, and 0.05 g/L, respectively. The lowest breakdown voltages at 1% breakdown for BN concentrations of 0.01 g/L, 0.025 g/L, and 0.05 g/L are 20.5 kV, 28.1 kV, and 35.48 kV, respectively. From the table, 1% breakdown voltage probability shows that the safest value is at 0.025 g/L $Fe_3O_4$ concentration. For $SiO_2$, and BN, only 0.05 g/L of the concentration exceeds 30 kV, which is the minimum standard AC breakdown voltage and others concentration failed. It is necessary to conduct more research on boron and silicon since the presence of CTAB has a detrimental influence on the breakdown voltage.

## V. DISCUSSION

Based on the research, Fig. 5 and Fig. 6 demonstrates that the average AC breakdown voltage of RBO with or without CTAB could only be slightly increased by the conductive nanoparticle iron. It was challenging to establish the optimal concentration for enhancing AC breakdown voltage since the agglomerations of nanoparticles in oil samples could not be controlled by increasing the volume concentration of nanoparticles [20], [20]. More study on this subject is needed to confirm the findings in the future. It has been discovered that silicon nanoparticle reduces the average AC breakdown voltage of RBO agreed with the previous study in [22]. The average AC breakdown voltages of RBO with or without CTAB for silicon have not improved, as shown by Fig. 5 and Fig. 6 from the current experiment.

Based on Fig. 5 and Fig. 6, the nanoparticle for boron might marginally raise the AC breakdown voltage with or without CTAB. Research on the effects of iron, silicon, and boron on the average AC breakdown voltage of other kinds of vegetable oils has not yet been conducted. It will need additional investigation at the molecular level to ascertain the negative effects of these nanoparticles on the average AC breakdown voltage of RBO.

While this needs more research, CTAB demonstrates that under this investigation, the AC breakdown voltage on each nanofluid RBO is reduced. According to past studies, CTAB is one of the most prominent surfactants that may be used to reduce the agglomeration and improve dispersion of the nanoparticles in mineral oil, palm oil, coconut oil, and soybean ester oil [7], [23], [24]. Previous studies on ZnO and $TiO_2$ nanofluids made from soybean and palm ester oils show that CTAB incorporation raises AC breakdown voltages. This is due to improved nanoparticle aggregation, which increases the capacity for charge trapping. [7], [24]. This could be because of the viscosity's effect and the restricted compatibility of CTAB with certain nanoparticles. The potential for these agglomerations to induce modest charge entrapment and distortion in the electric field may have some influence on the AC breakdown voltage [20], [22-24]. The high viscosities of RBO may also contribute to the suspension of nanoparticles, which would therefore prevent CTAB from having any discernible beneficial effect on AC breakdown voltages.

In general, the results of recent research indicate that the injection of nanoparticles at certain volumes concentrations might, with a 1% breakdown voltage probability, increase the AC breakdown voltage for RBO without CTAB, the largest improvement comes with iron. Practically speaking, increasing the AC breakdown voltage at the lowest probability may aid in future improvements to the design of transformers including vegetable-based nanofluids.

## VI. CONCLUSION

From this study, it shows that $Fe_3O_4$ nanoparticles are possibly able to enhance the dielectric performance of the insulation oil. BN shows a modest effect while $SiO_2$ reduces the breakdown voltage. From this research, it is also believed that only a small amount of $Fe_3O_4$concentration can help to improve the dielectric properties of insulation oil. It is found that the most optimum concentration of iron to be dispersed in RBO is 0.025 g/L as it shows a good performance with the highest breakdown voltage of 90.1 kV. The presence of CTAB as a surfactant in RBO nanofluid is not suitable as the existence of it in nanofluid in every concentration only shows degradation of the nanofluid dielectric strength. Hence, further knowledge is needed to confirm the impact iron oxide, silicon dioxide, and boron nitride on the AC breakdown voltage performance of vegetable oil. From normal probability distribution, the current research shows that the introduction of $Fe_3O_4$ at all volume concentrations tested could increase the AC breakdown voltage at 1% probability wither with or without CTAB. However, silicon and boron show negative impact on the AC breakdown voltage at 1% probability of RBO with and without CTAB.

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