Dielectric Strength Enhancement of Soybean Oil (FR3) with Nanoparticle Insulation: A Statistical Analysis

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ABSTRACT

This study investigates the influence of various magnetic nanoparticles on the dielectric Breakdown Voltage (BDV) of dielectric oils, specifically soybean-based oil (FR3). This study focuses on how different concentrations of iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3) nanoparticles affect the dielectric strength of the insulating fluid. The nanofluids were prepared using a two-step method with nanoparticle concentrations of 0.0003%, 0.008%, 0.016%, and 0.033% by volume in FR3 oil. The BDV tests were conducted using a mushroom-mushroom electrode configuration in accordance with IEC 60156 standard. Each nanofluid sample underwent 12 test iterations with a 10-min recovery period between measurements to ensure consistency and reliability. The experimental results revealed a notable enhancement in the dielectric breakdown strength of the nanofluids, indicating that the addition of nanoparticles can significantly improve the insulating properties of transformer oils. Statistical analysis was employed to validate the data and enhance the precision of the BDV readings. Among the tested samples, the Al_2O_3-based nanofluid demonstrated the highest BDV improvement, achieving a 41.62% increase. TiO_2 followed closely with a 40.16% enhancement, whereas Fe_3O_4 showed a 26.8% improvement. The concentration of TiO_2 nanoparticles has a significant effect on the BDV, supported by a strong and reliable regression model capable of predicting changes in the BDV based on the TiO_2 concentration. This model demonstrated a very strong correlation (R = 0.903), with 81.5% of the variation in the BDV explained by the changes in the TiO_2 concentration.

Keywords-dielectric properties; FR3 soybean oil; electrical insulation; high voltage engineering

I. INTRODUCTION

Mineral-based oil insulation has long been the industry standard for oil-immersed power transformers because of its effective dielectric properties, cooling capabilities, and cost efficiency. However, the rapid pace of urbanization and the rising demand for electrical energy have pushed power networks closer to their operational limits, resulting in a growing number of transformer failures. These incidents not only disrupt the power delivery, but also pose significant environmental and safety hazards. Transformer explosions involving mineral oil can release toxic gases, such as methane, and lead to oil spills, which may severely contaminate the soil and water in the surrounding area [1]. Consequently, there has been an increasing interest in the environmentally friendly alternatives to mineral oil.

Natural Ester (NE), a fully biodegradable dielectric fluid derived from vegetable oils, such as canola, rapeseed, soybean, sunflower, and palm oil, has emerged as a promising candidate. Since the 1990s, numerous studies have evaluated its application in power systems, either in its pure form, blended with mineral oils, or chemically modified to enhance its specific properties [2-5]. For example, modifying the palm kernel oil into alkyl esters with longer side chains has been shown to improve the breakdown strength over conventional mineral oil [6]. NE also offers better moisture tolerance and reduces pressboard aging due to its higher molecular solubility [7, 8].

Research has demonstrated that both conductive and semiconductive nanoparticles can be successfully dispersed in mineral and vegetable insulating oils to enhance their dielectric strength and thermal conductivity. Magnetic Fe_3O_4 nanoparticles, in particular, have been shown to increase the AC BDV of insulating oils, provided that the nanoparticles are well-dispersed within the oil [9-11]. Additionally, it has been documented that both mineral and vegetable insulating oils exhibit improved AC breakdown voltages and partial discharge inception voltages when modified with semiconductive TiO_2 nanoparticles [12]. Furthermore, the electrical properties and dispersion stability of three nanofluids prepared by dispersing Fe_3O_4, TiO_2, and Al_2O_3 nanoparticles in transformer oils have been explored to a certain extent [13-15].

The dielectric performance of nanofluids is strongly influenced by the nanoparticle size [16-18]. However, systematic and comparative studies specifically addressing how the particle size affects the breakdown and dielectric properties of vegetable oil-based nanofluids remain limited. This issue is critical for the application of such fluids in large power transformers. A major technical challenge lies in achieving stable dispersion, as nanoparticles tend to agglomerate in oil due to their high surface energy. Moreover, producing nanoparticles that are single-crystalline, uniformly shaped, and narrowly distributed in size is difficult, yet essential for accurately evaluating their influence on dielectric behavior.

Several models have been proposed to explain the enhanced breakdown characteristics of nanofluids [19-22]. However, these mechanisms often struggle to fully elucidate the influence of nanoparticle size on the BDV and dielectric properties of nanofluids. This gap highlights the need for more comprehensive studies that consider both the type and size of nanoparticles in various base fluids. In response to this, the present study investigated the influence of three types of nanoparticles, Fe_3O_4, TiO_2, and Al_2O_3, each with varying sizes and concentrations, on the AC-BDV of soybean oil (FR3), a biodegradable and eco-friendly insulating fluid. Given the growing demand for sustainable alternatives to mineral oil in power transformers, understanding the dielectric behavior of FR3-based nanofluids is becoming urgent. Statistical analyses, including the Weibull probability distribution and regression tests, were conducted to ensure the reliability and consistency of the experimental findings. This study not only addresses the unexplained effects of nanoparticle size, but also contributes to the development of environmentally friendly high-performance insulating fluids.

II. EXPERIMENTAL DETAILS

To understand the effect in the insulation properties of different nanoparticles and their concentration, the BDV was estimated for nanofluids with various particle volume concentrations, following IEC standards. These measurements contain sufficient information to determine the suitability of these nanoparticles and their concentration in enhancing the properties of nanomodified liquid insulation.

A. *Nanoparticle Preparation*

In this study, TiO_2, Al_2O_3, and Fe_3O_4 nanoparticles were utilized as dispersing agents in soybean oil (FR3). These nanoparticles were chosen for their unique properties, such as high thermal conductivity, stability, and magnetic characteristics, which are expected to enhance the performance of FR3 as an insulating medium. By incorporating these nanoparticles, the heat dissipation capability of the oil is anticipated to improve, thereby boosting its effectiveness in maintaining optimal operating temperatures. Moreover, the magnetic properties of Fe_3O_4 offer the potential for improved electromagnetic interference shielding, further benefiting the system's overall reliability. Before the nanoparticles were mixed into the oil, a drying stage was carried out to remove any moisture or contaminants attached to the surface of the nanoparticles. The drying process was performed using an oven at 200 °C for 2 h [23]. This temperature was chosen because it was sufficiently high to evaporate water without damaging the nanoparticle structure. The purpose of this drying process was to ensure that the nanoparticles were dry, allowing them to mix homogeneously with soybean oil (FR3). Proper drying also prevents moisture-related issues, such as agglomeration, which can negatively affect the dispersion and performance of nanoparticles in oil.

B. *Soybean Oil (FR3)-Based Nanofluid Preparation*

The preparation process of the soybean oil (FR3) nanofluid is illustrated in Figure 1, and involves several critical steps to ensure the stability and optimal performance of the final product. The procedure began with soybean oil (FR3), which was first filtered using filter paper to eliminate any particulate contaminants. Subsequently, the oil was heated in a convection oven to remove moisture, thus improving its dielectric properties. Parallel to this, the nanoparticles and surfactant materials were individually heated in a convection oven to eliminate moisture. This step is essential for enhancing the dispersion quality of the nanoparticles in the oil. After drying, the nanoparticles were mixed with a surfactant and a dispersant agent, followed by sonication.

Sonication was used to break down the agglomerates and ensure a uniform dispersion at the nanoscale. The resulting mixture was then magnetically stirred, which facilitated the evaporation of the excess dispersant and improved the homogeneity. To remove the entrapped gas bubbles that might affect the electrical insulation performance of the nanofluid, vacuum desiccation was applied. In the final stage, the pre-treated transformer oil was combined with the nanoparticle mixture, and another round of sonication was performed to ensure thorough dispersion. The end product was a stable nanofluid ready for testing or application in transformer systems. This comprehensive preparation method ensures minimal moisture content, effective nanoparticle dispersion, and the elimination of gas bubbles, which are all crucial parameters for achieving enhanced thermal and dielectric properties in transformer oil-based nanofluids.

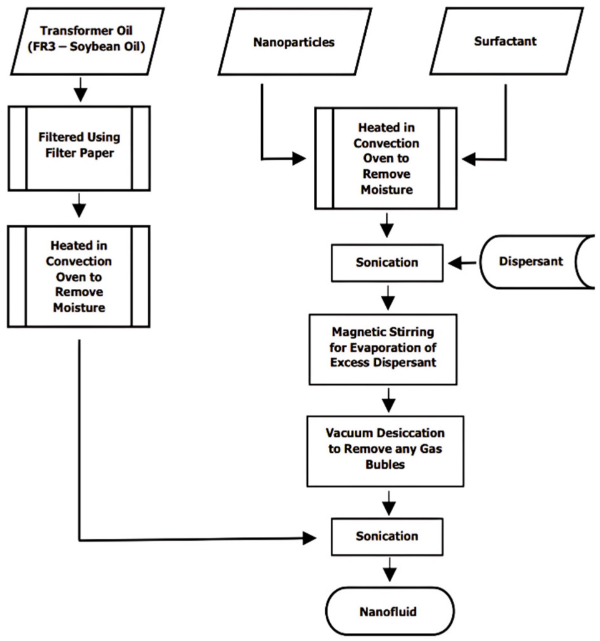


Fig. 1. Flowchart for the preparation of soybean oil (FR3)-based nanofluids.

C. BDV Tests

The BDV test on transformer oil is essential for assessing the quality and reliability of the oil as an insulating medium in transformers. This verifies that the oil has adequate dielectric strength to endure high voltages and identifies potential contamination or degradation that could impair insulation. The test is typically conducted following the IEC 60156 standard (Table I), which outlines the procedures for evaluating the dielectric strength of both the new and used insulating oils [24].

TABLE I. IEC 60156 STANDARD FOR BDV TESTS

Parameter	Description
Rate of voltage increase	2 kV/s to 5 kV/s
Test temperature	20 °C to 25 °C (room temperature)
Maximum voltage	80 kV
Criteria	The minimum standard for transformer oil is 30 kV
Test methods	Using a breakdown testing apparatus (test set)
Test voltages	Applied gradually until breakdown occurs

During the test, a sample of transformer oil was placed between two electrodes in a high-voltage test apparatus described in Figure 2, and voltage was applied gradually at a constant rate until breakdown occurred, as indicated by the electrical discharge or ignition. The voltage at which breakdown occurs is recorded as the BDV. This value reflects the oil's dielectric strength and its ability to function effectively as an insulating material under electrical stress.

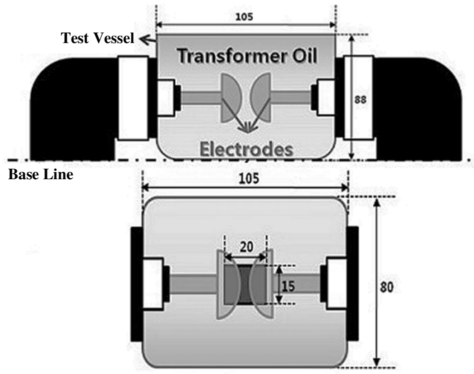


Fig. 2. The apparatus for testing the BDV of soybean oil (FR3)-based nanofluids.

The IEC standard sets minimum BDV thresholds. Oils that do not meet these limits need to be either replaced or purified. The main goal of the breakdown test is to ensure that transformer oil can provide reliable and safe insulation under normal operating conditions. In conclusion, conducting a BDV test on transformer oil according to IEC 60156 is essential for maintaining the transformer performance.

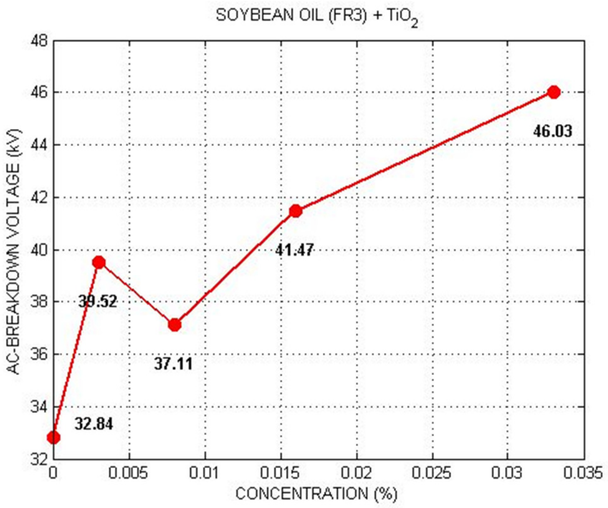
III. RESULTS AND ANALYSIS

This section presents the results of the BDV of soybean oil (FR3)-based insulating fluid, enhanced with Fe_3O_4, Al_2O_3, and TiO_2 nanoparticles. It is studied how each nanoparticle type and concentration affect the dielectric properties and breakdown voltage. The observed performance variations are linked to the nanoparticle characteristics, with statistical methods ensuring analytical validity and reliability.

A. BDV Test Results

The BDV test results are essential for evaluating the effectiveness of Fe_3O_4, Al_2O_3, and TiO_2 nanoparticles in enhancing the insulating performance of soybean oil (FR3). This section presents the breakdown voltages at various nanoparticle concentrations, emphasizing their impact on electrical properties. Tests were conducted under controlled conditions to ensure accuracy, and statistical analysis was used to identify the most effective concentrations. The findings offer insights into the mechanisms behind improved insulation and the potential use of nanoparticle-enhanced soybean oil in electrical systems.

Based on the BDV test results shown in Figure 3, the addition of Fe_3O_4, TiO_2, and Al_2O_3 particles to soybean oil (FR3) can increase its breakdown voltage, but the effect depends on the concentration of each material. At lower concentrations (around 0.003%-0.016%), all oils showed a significant increase in the breakdown voltage, indicating an improvement in the insulating properties of the oil. However, at higher concentrations (above 0.016%), the insulation performance decreased, indicating that there is an optimal concentration for each type of nanoparticle. The addition of particles at this optimal concentration produced the best performance in withstanding the electrical voltage before breakdown.



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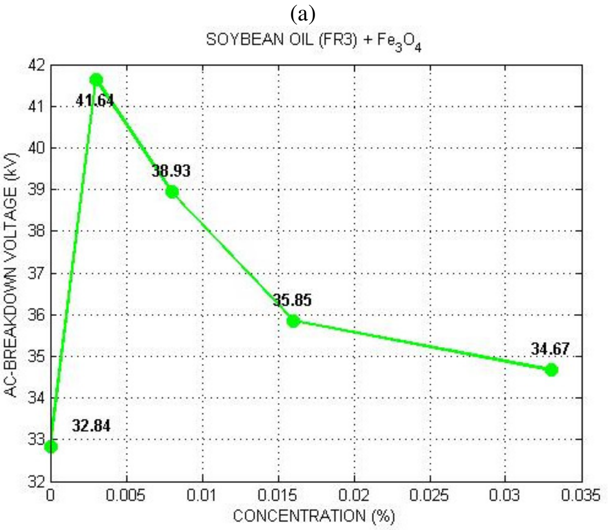

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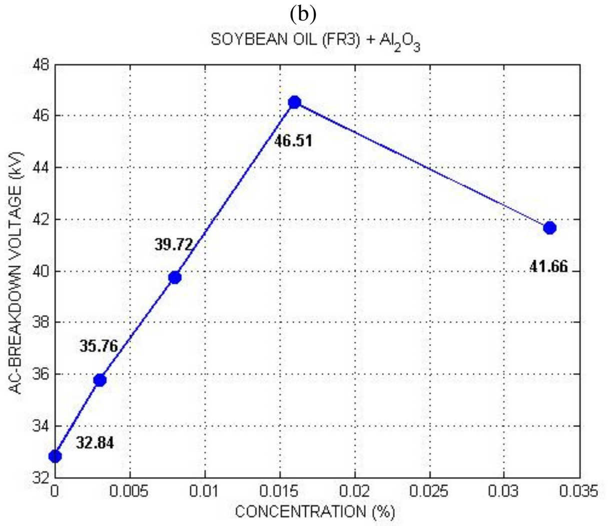

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Fig. 3. BDV test results for soybean oil (FR3)-based nanofluids: (a) TiO_2, (b) Fe_3O_4, and (c) Al_2O_3.

B. Regression Analysis

This section presents the results of the regression analysis to test the effect of nanoparticle concentration on the BDV of soybean oil (FR3). The data show that the BDV increases with the addition of nanoparticles. This relationship highlights the potential of nanoparticle additives to improve the dielectric strength of insulating fluids.

TABLE II. REGRESSION TEST ON TiO_2 NANOFLUIDS

Model summary

Model	R	R square	Adjusted R square	Std. error of the estimate
1	0.903[a]	0.815	0.753	2.44123

a. Predictors: (constant), nanoparticle (TiO_2) concentration

ANOVA[a]

Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	78.655	1	78.655	13.198	0.036[b]
	Residual	17.879	3	5.960		
	Total	96.534	4			

a. Dependent variable: BDV

b. Predictors: (constant), nanoparticle (TiO_2) concentration

TABLE III. REGRESSION TEST ON FE_3O_4 NANOFLUIDS

Model summary

Model	R	R square	Adjusted R square	Std. error of the estimate
1	0.294[a]	0.086	-0.218	4.06206

a. Predictors: (constant), nanoparticle (Fe_3O_4) concentration

ANOVA[a]

Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	4.669	1	4.669	0.283	0.632[b]
	Residual	49.501	3	16.500		
	Total	54.171	4			

a. Dependent variable: BDV

b. Predictors: (constant), nanoparticle (Fe_3O_4) concentration

TABLE IV. REGRESSION TEST ON AL_2O_3 NANOFLUIDS

Model summary

Model	R	R square	Adjusted R square	Std. error of the estimate
1	0.666[a]	0.443	0.257	4.55981

a. Predictors: (constant), nanoparticle (Al_2O_3) concentration

ANOVA[a]

Model		Sum of squares	df	Mean square	F	Sig.
1	Regression	49.618	1	49.618	2.386	0.220[b]
	Residual	62.376	3	20.792		
	Total	111.993	4			

a. Dependent variable: BDV

b. Predictors: (constant), nanoparticle (Al_2O_3) concentration

Based on the regression analysis in Table II, there is a very strong positive relationship between the concentration of TiO_2 nanoparticles and the BDV, as indicated by the correlation coefficient R of 0.903. This demonstrates that an increase in the TiO_2 concentration tends to result in a higher BDV. The coefficient of determination R^2 is 0.815, suggesting that approximately 81.5% of the variation in the BDV can be explained by the changes in the TiO_2 concentration. The adjusted R^2 value of 0.753 confirms that the model remains reliable even after considering the number of predictors and sample size, showing that it can be generalized well. The standard error of 2.44123 indicates a low level of prediction error, supporting the model's accuracy. Furthermore, the ANOVA results show an F-value of 13.198 with a p-value of

0.036, which is below the 0.05 significance level. This confirms that the regression model is statistically significant at a 95% confidence level. In summary, the concentration of TiO_2 had a significant and positive effect on the BDV, and the regression model provided strong predictive results.

Based on Table III, the relationship between the concentration of Fe_3O_4 nanoparticles and the BDV is very weak. This means that increasing or decreasing the amount of Fe_3O_4 has little to no effect on the BDV. Only approximately 8.6% of the changes in the BDV can be explained by the concentration of Fe_3O_4, whereas the remaining 91.4% is likely caused by other factors not included in the model. The negative adjusted R^2 value suggests that the model does not fit the data well and may even provide confusing results. The statistical test also shows that the model is not significant, meaning it cannot be trusted for making accurate predictions. In conclusion, the concentration of Fe_3O_4 nanoparticles does not have a meaningful impact on BDV, and the regression model is not a reliable tool for prediction. Based on Table IV, the relationship between the concentration of Al_2O_3 nanoparticles and BDV is relatively strong, but not very high. The correlation coefficient R of 0.666 shows that there is an effect, as the concentration of Al_2O_3 increases the BDV tends to increase as well. However, only about 44.3% of the change in BDV can be explained by the concentration of Al_2O_3. The remaining 55.7% is likely influenced by other factors not analyzed in this model. The Adjusted R^2 value of 0.257 indicates that the model is weaker after accounting for the number of data points and variables. This implies that the model is not generalizable. Additionally, the statistical test results show that the model is not significant because the p-value is greater than 0.05. In conclusion, although there is some effect of the Al_2O_3 concentration on the breakdown voltage, the model is not accurate or strong enough to be used as a reliable predictive tool.

C. *Correlation Tests*

Correlation tests were conducted to determine the effect of nanoparticle concentration on the BDV of soybean oil (FR3). Several nanoparticle concentrations, ranging from low to high, were adopted to assess how the addition of nanoparticles can either increase or decrease the BDV of the oil.

The data obtained from these tests were analyzed to identify trends and patterns that can serve as a reference for improving the quality of soybean oil (FR3) as a more efficient and reliable insulating fluid in transformer applications. This analysis also helps to understand the performance of oil under varying operational conditions, providing insights into potential improvements that can enhance the durability and longevity of transformers using soybean oil (FR3). In the correlation analysis summarized in Table V, a strong positive association was observed between the BDV and the concentration of TiO_2 nanoparticles in the nanofluid, with a Pearson correlation coefficient of 0.903, indicating a very strong linear relationship. The significance value of 0.036 confirms that this correlation is statistically significant at the 5% level, suggesting that increasing the concentration of TiO_2 nanoparticles enhances the BDV, thereby improving the electrical insulation performance of the nanofluid. In contrast, the correlation analysis presented in Table VI, which examines the relationship between the BDV and the concentration of Fe_3O_4 nanoparticles, revealed a weak negative correlation of -0.294 with a non-significant p-value of 0.632, indicating that this relationship might be due to random variation rather than a meaningful connection.

TABLE V. CORRELATION TEST ON TIO_2 NANOFLUIDS

Correlations

		BDV	**TiO_2 concentration**
BDV	Pearson correlation	1	0.903*
	Sig. (2-tailed)		0.036
	N	12	12
TiO_2 concentration	Pearson correlation	0.903*	1
	Sig. (2-tailed)	0.036	
	N	12	12

* Correlation is significant at the 0.05 level (2-tailed)

TABLE VI. CORRELATION TEST ON FE_3O_4 NANOFLUIDS

Correlations

		BDV	**Fe_3O_4 concentration**
BDV	Pearson correlation	1	-0.294*
	Sig. (2-tailed)		0.632
	N	12	12
Fe_3O_4 concentration	Pearson correlation	-0.294*	1
	Sig. (2-tailed)	0.632	
	N	12	12

* Correlation is significant at the 0.05 level (2-tailed)

TABLE VII. CORRELATION TEST ON AL_2O_3 NANOFLUIDS

Correlations

		BDV	**Al_2O_3 concentration**
BDV	Pearson correlation	1	0.666*
	Sig. (2-tailed)		0.220
	N	12	12
Al_2O_3 concentration	Pearson correlation	0.666*	1
	Sig. (2-tailed)	0.220	
	N	12	12

* Correlation is significant at the 0.05 level (2-tailed)

Similarly, Table VII displays a positive relationship between the BDV and the concentration of Al_2O_3 nanoparticles, with a Pearson correlation coefficient of 0.666. However, the p-value of 0.220 indicates that this correlation is not statistically significant at the 5% level, suggesting that while a positive trend exists, it is not conclusive. The correlation heatmap in Figure 4 exhibits the varying relationships between the nanoparticle concentration and BDV in TiO_2, Fe_2O_3, and Al_2O_3-based nanofluids. TiO_2 exhibited a strong positive correlation, highlighting its effectiveness in enhancing the dielectric strength. Fe_2O_3 showed a weak negative correlation, possibly due to particle agglomeration or increased charge carrier density, weakening its insulating properties. Al_2O_3 had a moderate positive correlation, suggesting that it improves the BDV, although less significantly than TiO_2. These results emphasize the important role of nanoparticle type in nanofluid performance, with TiO_2 being the most promising material for improving the dielectric strength.

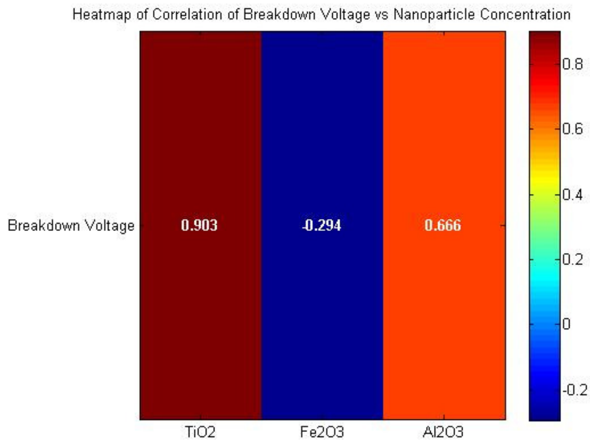
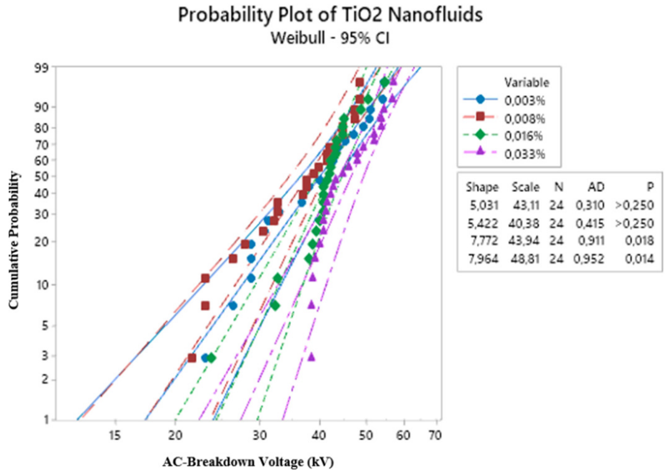


Fig. 4. Correlation heatmap between nanofluids.

D. Weibull Probability Analysis

To evaluate the transformer insulation reliability, the Weibull probability method was applied to predict the breakdown probability in FR3-nanofluid samples [25, 26]. Figure 5 presents the BDV Weibull plot at 1%, 10%, and 50% cumulative probabilities, indicating the minimum reliability, risk level, and average BDV. This probabilistic approach helps engineers assess the safety margins and optimize the insulation materials and system designs to enhance the reliability and lifespan.

Based on Figure 5, the Weibull probability plot analysis of the TiO_2, Fe_3O_4, and Al_2O_3 nanofluids at different concentrations (0.003%, 0.008%, 0.016%, and 0.033%) provides a clear picture of the reliability of each material. For the TiO_2 nanofluids, all concentrations showed a shape parameter (β) greater than 1, which means that the failure rate increased over time owing to typical wear-out mechanisms. As the concentration of TiO_2 increased, both the shape and scale parameters increased, with the 0.033% concentration showing the best endurance, although there was a slight statistical deviation ($p < 0.05$). In the case of Fe_3O_4 nanofluids, even though the 0.003% concentration had the highest shape parameter ($\beta = 8.632$), the very low p-value ($p < 0.010$) indicated a poor fit to the Weibull model. On the other hand, the 0.008% and 0.016% concentrations showed the best statistical performance, with high scale parameters and p-values above 0.250, indicating improved stability and reliability. For Al_2O_3 nanofluids, all concentrations fit well with the Weibull distribution ($\beta > 1$), especially at 0.003%, 0.016%, and 0.033%, which have p-values above 0.250. The 0.016% concentration stands out with the highest scale parameter ($\eta = 49.76$), indicating the best reliability among all the samples. Overall, this analysis shows that increasing the nanofluid concentration tends to improve the system reliability and stability, though the optimal concentration varies for each material. The optimal concentrations were 0.033% for TiO_2, 0.008–0.016% for Fe_3O_4, and 0.016% for Al_2O_3.



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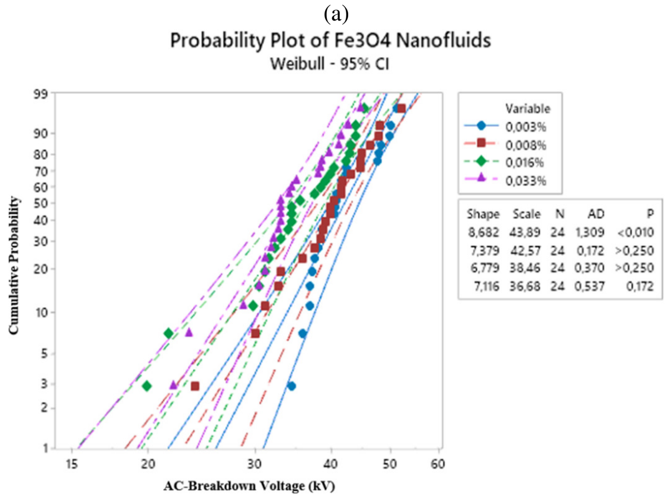

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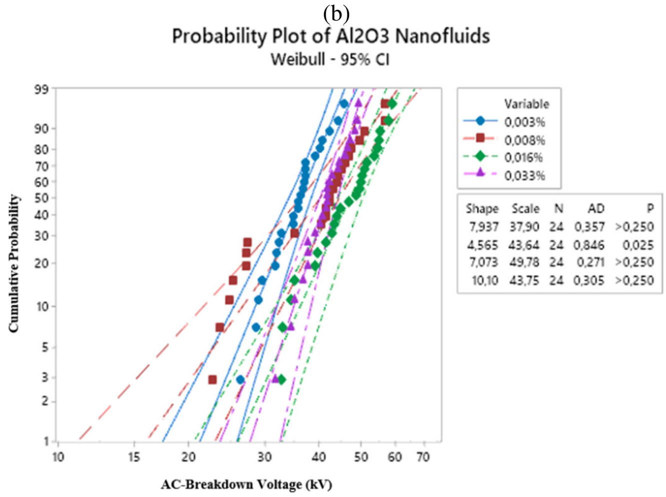

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Fig. 5. Weibull probability plot of the BDV of (a) TiO_2, (b) Fe_3O_4, and (c) Al_2O_3.

Table VIII presents the results of the hypothesis test to check the conformity of various nanofluid samples to the Weibull distribution model, based on p-values (ρ). The results show that most samples, including those based on TiO_2, Fe_3O_4, and Al_2O_3, conform to the Weibull distribution, as indicated by p-values greater than 0.250. For TiO_2-based nanofluids, all four concentrations followed the Weibull distribution, although the 0.016% and 0.033% concentrations showed slightly lower p-values (0.018 and 0.014, respectively), indicating a slight deviation but still within acceptable limits. The Fe_3O_4 samples exhibited similar behavior, with three of the four concentrations accepted. However, the 0.003% Fe_3O_4 sample is rejected ($p < 0.010$), indicating a significant deviation from the Weibull model and suggesting that this formulation may not be suitable for Weibull-based reliability analysis. In contrast, all the Al_2O_3-based nanofluid concentrations conformed to the Weibull distribution. The 0.008% sample had a p-value of 0.025, indicating a weaker fit than the other concentrations, but it was still statistically acceptable. The other Al_2O_3 concentrations showed high p-values (> 0.250), indicating a strong agreement with the Weibull model. Overall, the hypothesis test confirmed that most nanofluid formulations, particularly those based on Al_2O_3 and TiO_2, are statistically suitable for modeling using the Weibull distribution. The only exception is the 0.003% Fe_3O_4 sample, which shows significant deviation and may require alternative modeling approaches. Further research is proposed to refine the modeling of Fe_3O_4 based nanofluids.

TABLE VIII. HYPOTHESIS TEST OF CONFORMITY TO WEIBULL DISTRIBUTION

Sample	ρ	Conformity to Weibull distribution
FR3-TiO_2 (0.003%)	> 0.250	Accepted
FR3-TiO_2 (0.008%)	> 0.250	Accepted
FR3-TiO_2 (0.016%)	0.018	Accepted
FR3-TiO_2 (0.033%)	0.014	Accepted
FR3-Fe_3O_4 (0.003%)	< 0.010	Rejected
FR3-Fe_3O_4 (0.008%)	> 0.250	Accepted
FR3-Fe_3O_4 (0.016%)	> 0.250	Accepted
FR3-Fe_3O_4 (0.033%)	0.172	Accepted
FR3-Al_2O_3 (0.003%)	> 0.250	Accepted
FR3-Al_2O_3 (0.008%)	0.025	Accepted
FR3-Al_2O_3 (0.016%)	> 0.250	Accepted
FR3-Al_2O_3 (0.033%)	> 0.250	Accepted

E. Discussion

Soybean (FR3) nanofluids, derived from vegetable-based dielectric fluids, have garnered significant attention for their application in high-voltage insulation systems. Originally developed by Cargill, FR3 is a biodegradable and fire-resistant insulating fluid widely utilized in transformers due to its environmental and safety advantages. The incorporation of nanoparticles into soybean oil (FR3), forming what is known as nanofluids, has been shown to enhance key dielectric properties, particularly the breakdown voltage. Nanoparticles, such as Fe_3O_4, TiO_2, and Al_2O_3, contribute to this improvement by reducing the mean free path of the electrons. These particles scatter and absorb electrons, thereby lowering their kinetic energy and mitigating the risk of electrical discharges [27-29].

Optimal enhancement in the BDV is typically observed at specific nanoparticle concentrations, ranging from approximately 0.016% by weight for Al_2O_3 to 0.033% for TiO_2. However, the benefits may diminish beyond these concentrations owing to nanoparticle agglomeration, which can disrupt the uniform dispersion and degrade the fluid performance. Additionally, nanoparticles introduce a physical barrier that impedes the movement of free electrons and delays the formation of streamer ionized conductive channels that can initiate breakdown events [30-35].

In addition to improving the BDV, the nanofluids offer stable performance over long operational periods and provide significant environmental advantages compared with conventional mineral transformer oils. One of the main challenges in their application is maintaining a stable nanoparticle dispersion. Poor dispersion can lead to agglomeration, which negatively impacts the BDV and overall dielectric performance [36-38]. Ensuring compatibility between nanofluids and internal transformer components, such as insulation materials, is essential to avoid long-term degradation [39, 40]. Experimental studies have shown that incorporating nanoparticles, like Al_2O_3 or TiO_2, can enhance BDV by 10–30% compared to pure soybean oil, with performance improvements influenced by the nanoparticle size and distribution [41-45]. In the case of the nanofluid illustrated in Figure 6, the nanoparticles serve as barriers that hinder the charge movement between the electrodes by reducing their velocity. This effect is often attributed to the induction phenomenon, which decreases the overall mobility of charges. The resulting reduction in the charge velocity contributes to a decline in electrical conductivity [46, 47].

The discussion highlights that the incorporation of nanoparticles into natural insulating oils, such as soybean oil (FR3) and palm oil [48], significantly enhances the dielectric performance, with the effectiveness largely depending on the type and concentration of nanoparticles. Titanium dioxide (TiO_2) was identified as the most effective among the tested nanoparticles, showing statistically significant improvement in BDV at optimal concentrations (up to 0.033%), with a strong positive correlation ($R = 0.903$) and high reliability confirmed by Weibull analysis. In contrast, iron oxide (Fe_3O_4), being conductive in nature, was only effective at intermediate concentrations and exhibited reduced dielectric performance at higher concentrations due to increased electrical conductivity, tan delta, and partial discharge activity, as supported by its weak and statistically insignificant correlation with BDV [49]. Aluminum oxide demonstrated moderate performance, showing a consistent fit with the Weibull distribution but lacking statistical significance in the regression model, indicating limited generalizability.

Furthermore, the presence of natural oleic acid in vegetable-based oils acts as a surfactant, promoting better dispersion of nanoparticles and reducing the risk of agglomeration, which is critical for maintaining the nanofluid stability. Therefore, semiconductive nanoparticles, such as TiO_2, are more suitable for improving the dielectric reliability when applied at controlled concentrations, whereas the use of conductive nanoparticles, such as Fe_3O_4, requires careful management to avoid undesirable effects. As a result, nanofluids can achieve improved dielectric behavior, making them viable for insulation applications. This is further supported by the BDV results at a 10% risk level ($U_{10\%}$), where Fe_3O_4-based nanofluids demonstrated superior ability to suppress partial discharge and streamer propagation, likely due to their higher electronegativity, enabling better charge trapping compared to Al_2O_3 and TiO_2.

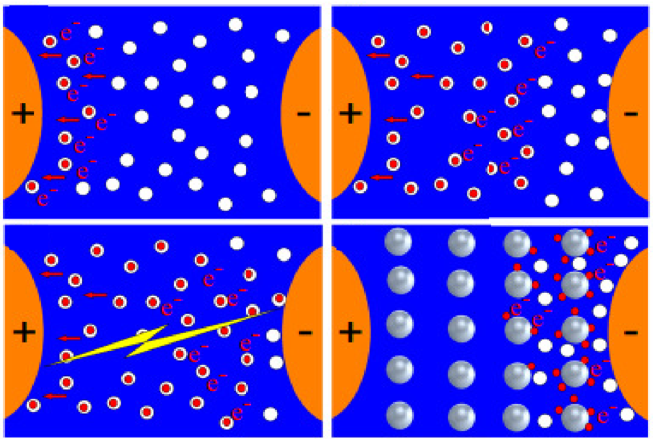

Fig. 6. Illustration of the movement of charges in FR3-Nanofluids, adapted from [50].

IV. CONCLUSIONS

The dielectric properties of insulating oils are vital for ensuring the performance and reliability of power transformers. This study investigated the effects of Fe_3O_4, TiO_2, and Al_2O_3 nanoparticles dispersed in soybean oil (FR3), demonstrating that nanofluids can enhance the breakdown voltage, especially at low concentrations (0.003%–0.016%). Beyond this range, the performance declined due to likely nanoparticle agglomeration, indicating the importance of optimizing the concentration levels.

The TiO_2 nanoparticles showed the most promising results, with a strong positive correlation to Breakdown Voltage (BDV) ($R = 0.903$; $R^2 = 0.815$), supported by statistical significance ($p = 0.036$). This highlights the model's robustness and predictive reliability. In contrast, Fe_3O_4 exhibited a weak and statistically insignificant correlation ($R = -0.294$; $p = 0.632$), suggesting its limited effectiveness. Al_2O_3 showed moderate correlation ($R = 0.666$), though not statistically significant ($p = 0.220$), indicating some improvement but reduced model generalizability. The Weibull probability analysis further confirmed these results. The TiO_2 nanofluids displayed increasing reliability with concentration, especially at 0.033%. Fe_3O_4 performed best at 0.008%–0.016%, whereas Al_2O_3 nanofluids exhibited a consistently good fit, with peak reliability at 0.016%.

In summary, the nanoparticle-infused FR3 oils exhibited enhanced dielectric strength, with TiO_2 emerging as the most effective and statistically reliable additive. Future research should refine the concentration ranges and explore alternative nanoparticle-oil combinations to optimize the transformer oil performance and long-term stability.

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