Analysis of Breakdown Characteristics in Nanofluid Insulation Materials with Metal Particle Contamination

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***Abstract*—Optimal insulation in transformers is essential to maintain their performance and reliability. However, insulation-related problems, particularly transformer oil contamination, often result in premature transformer failure. To address this issue, a solution has been proposed in the form of a nanofluid, a mixture of transformer oil, and nanoparticles. This study aims to investigate the impact of metal particle contamination on the breakdown and levitation voltage characteristics of nanofluids as liquid insulating materials. The nanofluids were prepared by mixing mineral oil with Fe_3O_4 nanoparticles at three different concentrations. Tests were conducted to evaluate the AC breakdown and levitation voltages for various contaminant metal particle sizes. The experimental results demonstrate that contaminant particle size has a significant impact on the breakdown voltage. The nanofluid with a concentration of 0.008% Fe_3O_4 exhibited superior breakdown voltage performance compared to mineral oil and 0.016% Fe_3O_4 nanofluid. Furthermore, an increase in the levitation stress was observed as the contaminant particle size increased. The findings of this study emphasize the importance of controlling contamination and selecting the appropriate concentration of nanoparticles to enhance transformer insulation performance. This study also highlights the necessity of monitoring the size of contaminant particles to prevent potential damage. Consequently, this study makes a significant contribution to the advancement of more reliable and efficient transformer insulation technology.**

***Keywords*— breakdown voltage, Fe_3O_4 nanoparticles, metal particle contaminants, nanofluid, transformer oil.**

I. INTRODUCTION

Transformers are electrical apparatuses that alter voltages to convey electrical power in power transmission and distribution systems. Consequently, it is of utmost importance that they operate at their optimal capacity, as power systems are inextricably linked to the functionality of transformers in the transfer of electrical power [1]. Transformers are comprised of essential components, including transformer oil, which serves as an insulator and cooling agent [2]. This oil separates the conductor from a part that is not under voltage, or between conductors with different voltages. [3]. Ensuring proper functioning of transformers is imperative for the stability and reliability of power networks, highlighting the significance of effective maintenance and insulation practices.

The data shows that transformers often fail long before the end of their expected lifetime. The average service life of transformers that have failed owing to dielectric insulation problems is only approximately 17.8 years, while the expected life is between 35 and 40 years. In addition, 75% of high-voltage transformer failures are caused by insulation problems [4]. Most transformers use mineral oil as a liquid insulating medium. This mineral oil is difficult for microorganisms to decompose and is prone to fire [5]. Long-term use of transformers can cause a decrease in the dielectric characteristics of transformer oil, resulting in insulation failure and eventual electrical breakdown [6]. The contamination of transformer oil is problematic because it can cause failure and reduce its dielectric strength. [7].

Recent research has developed nanoparticle technology that can be incorporated into liquid insulating materials, particularly transformer oils. These nanoparticles are distributed and assembled in the form of aggregates, where the insulating oil particles are strongly bonded or fused with the nanoparticles to form nanofluids. The purpose of this nanofluid is to provide a faster cooling process and to improve the dielectric quality of the insulating material to increase the breakdown voltage [8]–[15]. Fe_3O_4 nanoparticles are often researched for nanofluids because they show an increase in dielectric strength when mixed with transformer insulating oil [16]. Although nanofluid technology has the potential to be applied to transformers, further research is required to fully understand the implications of high electric fields on nanofluid performance, durability of nanofluid stabilization, and impact of real operating temperatures. High electric fields in transformer oil can lead to the production of partial discharges and a reduction in breakdown voltage [17].

Despite a number of studies, there remains a research gap regarding the effect of contaminants on transformer oil. Contamination can result in the failure of transformer oil,

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leading to a reduction in its dielectric strength. For instance, solid particle contaminants within an electrical apparatus may originate from the deterioration of transformer components, including transformer windings, transformer iron cores, transformer bodies, or solid particles that may gain access to the apparatus during the installation and maintenance of the equipment, which may potentially affect the breakdown voltage. This indicates the necessity for further research to comprehend and address the influence of this contamination with the objective of enhancing the dependability and functionality of liquid insulating materials in transformers.

This study investigates the impact of metal particle contamination on the breakdown and levitation stress characteristics of a nanofluidic insulating material, which is a combination of mineral oil and Fe_3O_4 nanoparticles. This research will focus on two main aspects: the variation in the concentration of Fe_3O_4 nanoparticles and the variation in the size of the metal particles. The principal advantage of this research lies in the comprehensive approach used to examine the effect of metal particle contamination on the performance of nanofluids as insulating materials. The findings of this research are anticipated to not only enhance transformer performance and reliability but also pave the way for novel advancements in liquid insulating material technology. By proposing nanofluids as a potential solution to future insulation challenges, this research is expected to make a significant contribution to developments in the field of transformers and electrical insulation technology.

II. METHODS

A. Development of Nanofluids

The nanofluid manufacturing process begins with the use of pure mineral oil as the base oil. The first step was to filter the mineral oil to remove any small particles that may be present. Filtration was performed using a membrane filter with a pore size of 0.2 µm, ensuring that the oil used was completely pure and free from contaminants. This pivotal stage establishes a framework for subsequent manufacturing processes, underscoring the significance of unadulterated oil as a cornerstone for nanofluid production.

After filtration, the mineral oil was dried to remove any residual moisture and impurities. The drying process was performed at 90°C for 24 h in a vacuum chamber at a pressure of 90 kPa. Drying under vacuum is essential to ensure that the oil is completely dry and ready to be mixed with nanoparticles without any contamination from water or other impurities [18].

Iron Oxide Nanoparticles (Fe_3O_4) are used to blend mineral oils. These nanoparticles were chosen because they have good magnetic and dielectric properties, which can improve the performance of the transformer oil. The concentration of nanoparticles significantly affects the dielectric properties of the nanofluid; therefore, various concentrations were used to examine their effects. The concentration of Fe_3O_4 nanoparticles was varied in three doses: 10, 50, and 100 mg. To ensure accuracy, nanoparticle weighing was performed using a precision electronic balance. This meticulous approach highlights the significance of precise dosing in the formulation of nanofluids and paves the way for enhanced transformer insulation and efficiency.

Based on previous research [19], the virgin oil and nanoparticles were placed in a vacuum chamber with a pressure of 90 kPa for 24 h to be dried at temperatures of 80°C and 300°C, respectively. Subsequently, the nanoparticles were dispersed in virgin oil and mixed using a magnetic stirrer for 30 min at a constant speed. This process aims to ensure that the nanofluid is well-mixed and produces minimal sediment. To achieve optimal stabilization, the nanofluid was sonicated in an ultrasonic bath for 30 min. Once these processes were complete, the Fe_3O_4 nanofluid was ready for use. The design and details of the nanofluid manufacturing process are shown in Fig 1.

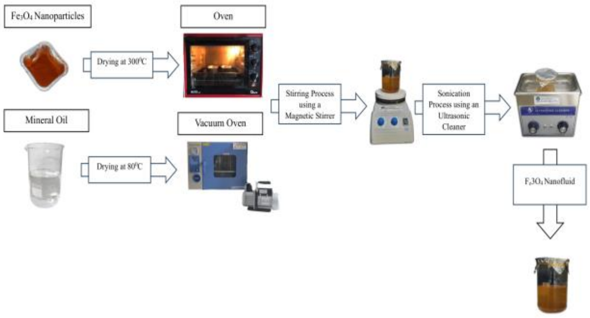

Fig. 1 Nanofluda preparation process

B. Breakdown Characteristic Investigations

Two breakdown characteristics are discussed in this study: the breakdown voltage and levitation voltage. Breakdown voltage is a condition in which the dielectric strength of an insulating material cannot withstand the electrical stress resulting from a certain voltage. The levitation voltage shows a situation in which the electrostatic force between the particle and the surrounding oil can oppose the gravitational force of the particle and cause the particle to float or become suspended in the oil. This test was conducted at the High-Voltage Laboratory of the Department of Electrical Engineering, Sepuluh Nopember Institute of Technology. An AC high-voltage test transformer was connected to the test medium, which consisted of two pairs of test electrodes with a distance of 10 mm between the electrodes immersed in 150 ml of Fe_3O_4 nanofluid. This nanofluid was prepared by mixing 150 ml of transformer oil with three different concentrations of Fe_3O_4 nanoparticles. The design and test media are shown in Fig 2.

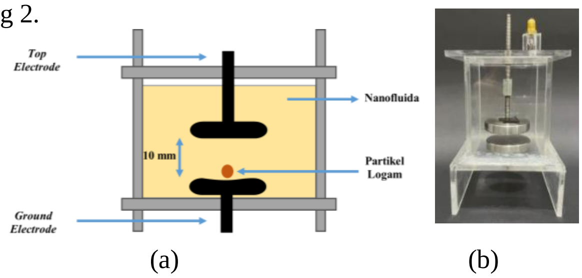

Fig. 2 (a) Design of the test chamber for free metal particles (b) Test chamber setup for free metal particles

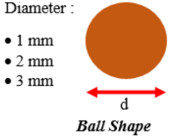

Fig. 3 The sizes of the metal ball particles

To assess the impact of metal contaminants, a metal ball particles made from copper with 3 different sizes were employed in the experiment, as illustrated in Fig 3. The metal ball particle were positioned above the ground electrode as free particle. This configuration was utilized to evaluate the influence of incorporating Fe_3O_4 nanoparticles into transformer oil as a liquid insulator in transformers, as well as the impact of contamination on the breakdown voltage characteristics.

C. Weibull Analysis

The Weibull distribution was employed to analyze the probability of failure. To generate a Weibull probability plot, it is necessary to provide scale and shape parameters as functions.

$$f(t)=1-exp(-t/\propto)\beta \tag{1}$$

The cumulative distribution function (CDF) of the Weibull probability for each random variable (t) is denoted by f(t). In this study, f(t) represents the CDF of the breakdown voltage probability, with t denoting the AC breakdown voltage, α representing the scale parameter, and β denoting the shape parameter. The plot position estimation for good, simple, and fast data resolution for the most probable cumulative percent failure with the Bernard approximation approach in determining the median rank is expressed in equation (2).

$$RM = \frac{j-0.3}{N+0.4}\, x\ 100 \tag{2}$$

The sample size, N, is defined as the vertical axis, while the sample order, j, is defined as the horizontal axis. The cumulative percent failure is depicted on the vertical axis, while the experimental data (t) is depicted on the horizontal axis. The sample size, N, is defined as the number of samples, and the sample order, j, is defined as the order in which the samples are taken.

Once the RM value has been obtained, it is plotted on the Weibull graph, with the y-axis representing the cumulative percent failure and the x-axis representing the experimental data (t).

The scale parameter (α) can be determined by means of linear regression of the following two equations:

$$\ln(t) \tag{3}$$

$$\ln(\ln(1/(1-RM))) \tag{4}$$

The linear equation of the regression result between the two equations is written in the form y = mx + b, where m represents the scale parameter (α). To calculate the shape parameter (β), the following equation can be employed:

$$\beta=\exp(-b/m) \tag{5}$$

The values of b and m are derived from the linear regression results between equations (3) and (4).

III. RESULTS AND DISCUSSION

A. AC breakdown voltage test result

A breakdown voltage test was conducted to compare the dielectric qualities of mineral oil and Fe_3O_4 nanofluids used as liquid insulating materials. In this study, the concentration of Fe_3O_4 nanoparticles was varied into three levels, namely 10 mg, 50 mg, and 100 mg, to determine the effect of concentration variation on the breakdown voltage. To simulate real-world contamination scenarios, metal ball particles of varying sizes were introduced into the sample. The objective of this study was to assess the impact of metal particles on the dielectric quality of mineral oil and Fe_3O_4 nanofluids. A total of 16 data retrievals were conducted during the test, which were then used as the basis for calculating the average, lowest, and highest values for each test sample. The comprehensive breakdown voltage test, which incorporated variations in the Fe_3O_4 nanoparticle concentration and simulated metal particle contamination, provided valuable insights into the dielectric properties of mineral oil and Fe_3O_4 nanofluids. This study contributes to a deeper understanding of how different factors influence the breakdown voltage and offers potential advancements in liquid insulation materials for transformer applications.

TABLE I. TEST SAMPLE DATA

Mineral Oil	MO
Mineral Oil with metal ball 1 mm	MO/MB-1
Mineral Oil with metal ball 2 mm	MO/MB-2
Mineral Oil with metal ball 3 mm	MO/MB-3
0.008% Fe_3O_4 Nanofluid	NF1
0.008% Fe_3O_4 Nanofluid with metal ball 1 mm	NF1/MB-1
0.008% Fe_3O_4 Nanofluid with metal ball 2 mm	NF1/MB-2
0.008% Fe_3O_4 Nanofluid with metal ball 3 mm	NF1/MB-3
0.016% Fe_3O_4 Nanofluid	NF2
0.016% Fe_3O_4 Nanofluid with metal ball 1 mm	NF2/MB-1
0.016% Fe_3O_4 Nanofluid with metal ball 2 mm	NF2/MB-2
0.016% Fe_3O_4 Nanofluid with metal ball 3 mm	NF2/MB-3

Table I. contains test sample data with 12 sample variations consisting of mineral oil, 0.008% Fe3O4 nanofluid and 0.016% Fe3O4 nanofluid without or with contaminants. In Figure 4-6. shows the average, lowest and highest values of AC breakdown voltage for each test sample. The AC breakdown voltage in mineral oil and nanofluids with contaminants has decreased compared to those without contaminants. The average AC breakdown voltage value of MO/MB-1 decreased by 25.86%, then MO/MB-2 experienced a decrease of 39.29%, and MO/MB-3 experienced the furthest decrease of 53.29% from the average breakdown voltage value, AC MO. In the case of NF1, there was a decrease in the AC breakdown voltage value of 23.01%, 27.99% and 38.6% for NF1/MB-1, NF1/MB-2 and NF1/MB-3. In the case of NF2, there was a decrease in the AC breakdown voltage value of 21.26%, 29.25% and 42.24% for NF2/MB-1, NF2/MB-2 and NF2/MB-3. Compared to MO, the overall AC breakdown voltage values of NF1 and NF2 increased. This indicates that the nanofluid Fe_3O_4, as a liquid insulating material, has a superior dielectric ability compared to mineral oil. While the overall AC breakdown voltage value of NF2 decreased compared to NF1,this indicates that the 0.008% Fe_3O_4 nanofluid represents the peak value or saturation point, such

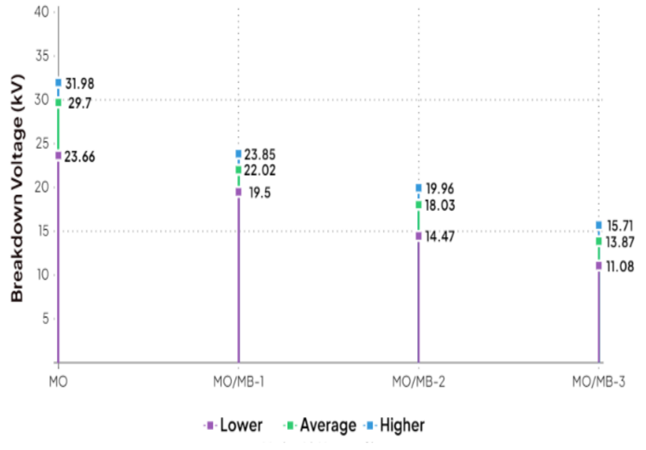

Fig. 4 AC breakdown voltage of mineral oil

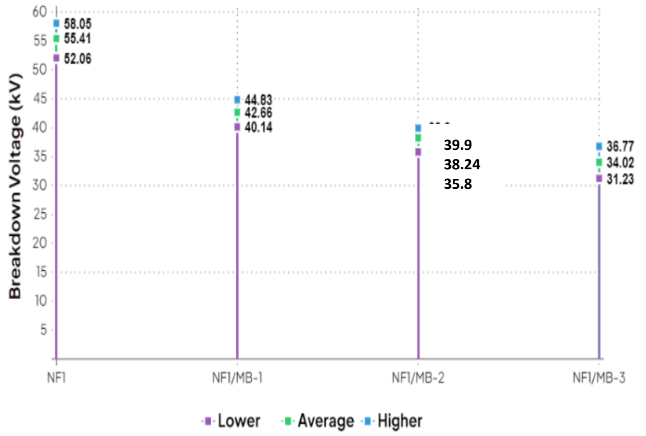

Fig. 5 AC breakdown voltage of 0.008% Fe_3O_4 Nanofluid

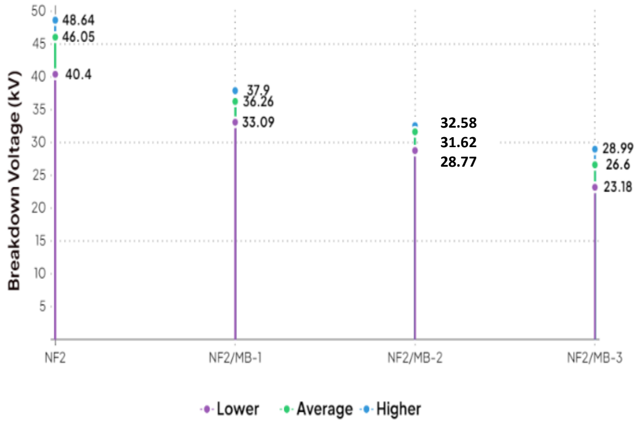

Fig. 7 AC breakdown voltage of 0.016% Fe_3O_4 Nanofluid

that the 0.016% Fe_3O_4 nanofluid experiences a decrease in dielectricity.

The results of this test demonstrate that an increase in contaminant particle size is associated with a reduction in AC breakdown voltage. There is a notable discrepancy in the extent of the reduction in the AC breakdown voltage observed in contaminated mineral oil, with a comparatively modest decline observed in contaminated nanofluids.

B. Weibull analysis of AC breakdown test results

Figures 7-9 illustrate the Weibull probability plots of AC breakdown voltage in mineral oil, 0.008% Fe_3O_4 Nanofluid, and 0.016% Fe_3O_4 Nanofluid, respectively, with 1 mm, 2 mm, and 3 mm metal ball particle contamination, with probability percentage up to 95%.

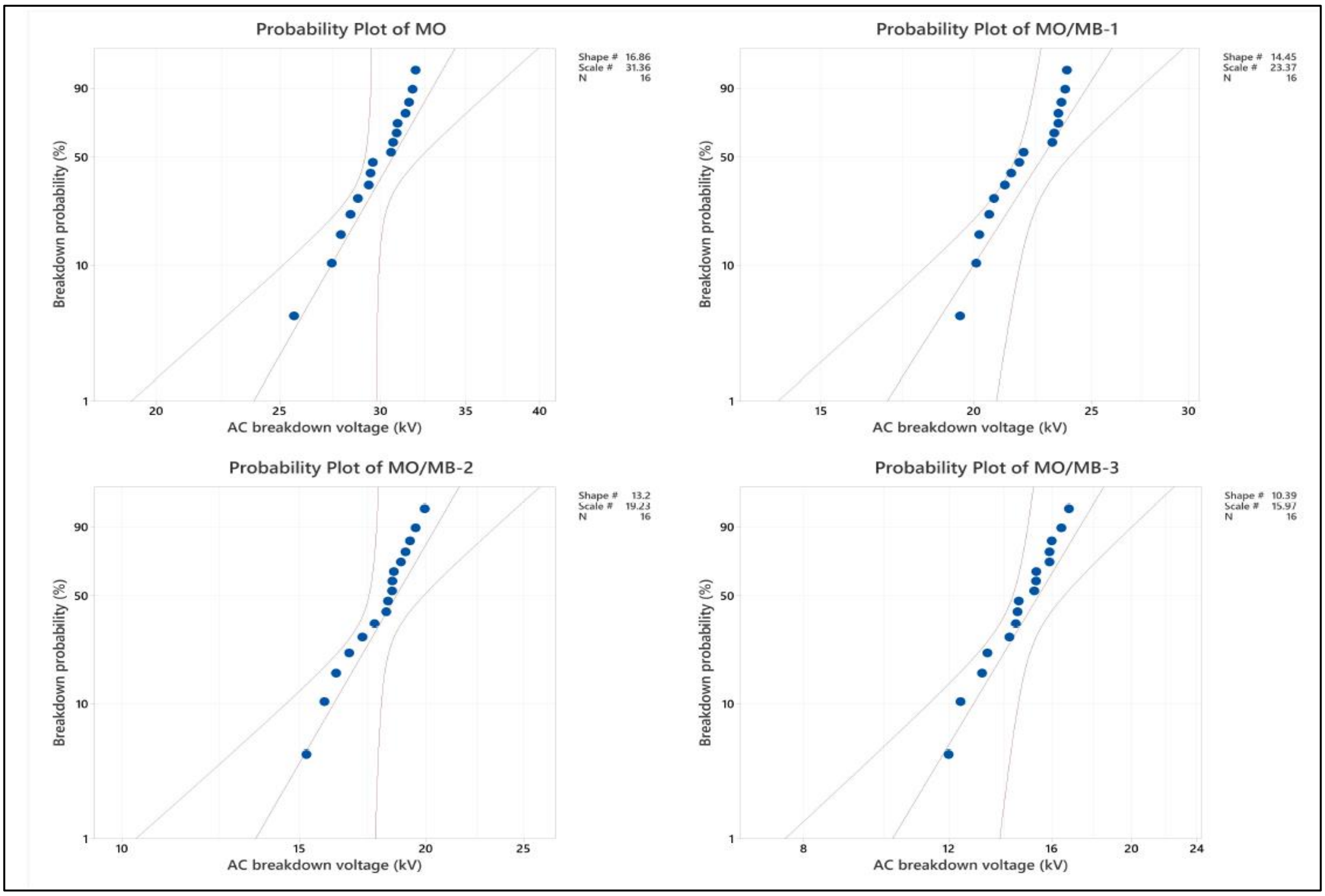

Fig. 6 Weibull plot of AC breakdown voltage : Mineral oil (MO), Mineral oil with metal ball 1 mm (MO/MB-1), Mineral oil with metal ball 2 mm (MO/MB-2), Mineral oil with metal ball 3 mm (MO/MB-3).

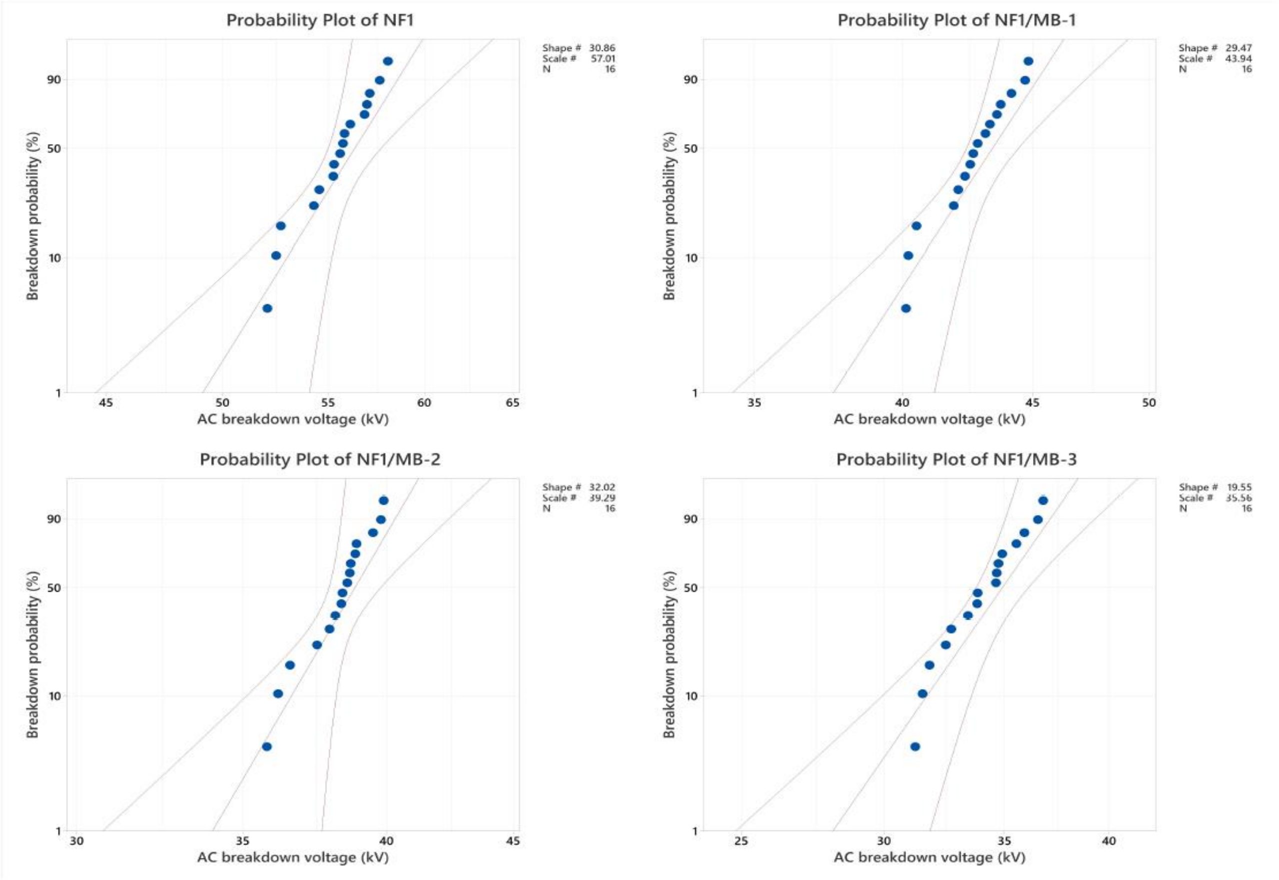

Fig. 8 Weibull plot of AC breakdown voltage : 0.008% Fe_3O_4 Nanofluid (NF1), 0.008% Fe_3O_4 Nanofluid with metal ball 1 mm (NF1/MB-1), 0.008% Fe_3O_4 Nanofluid with metal ball 2 mm (NF1/MB-2), 0.008% Fe_3O_4 Nanofluid with metal ball 3 mm (NF1/MB-3).

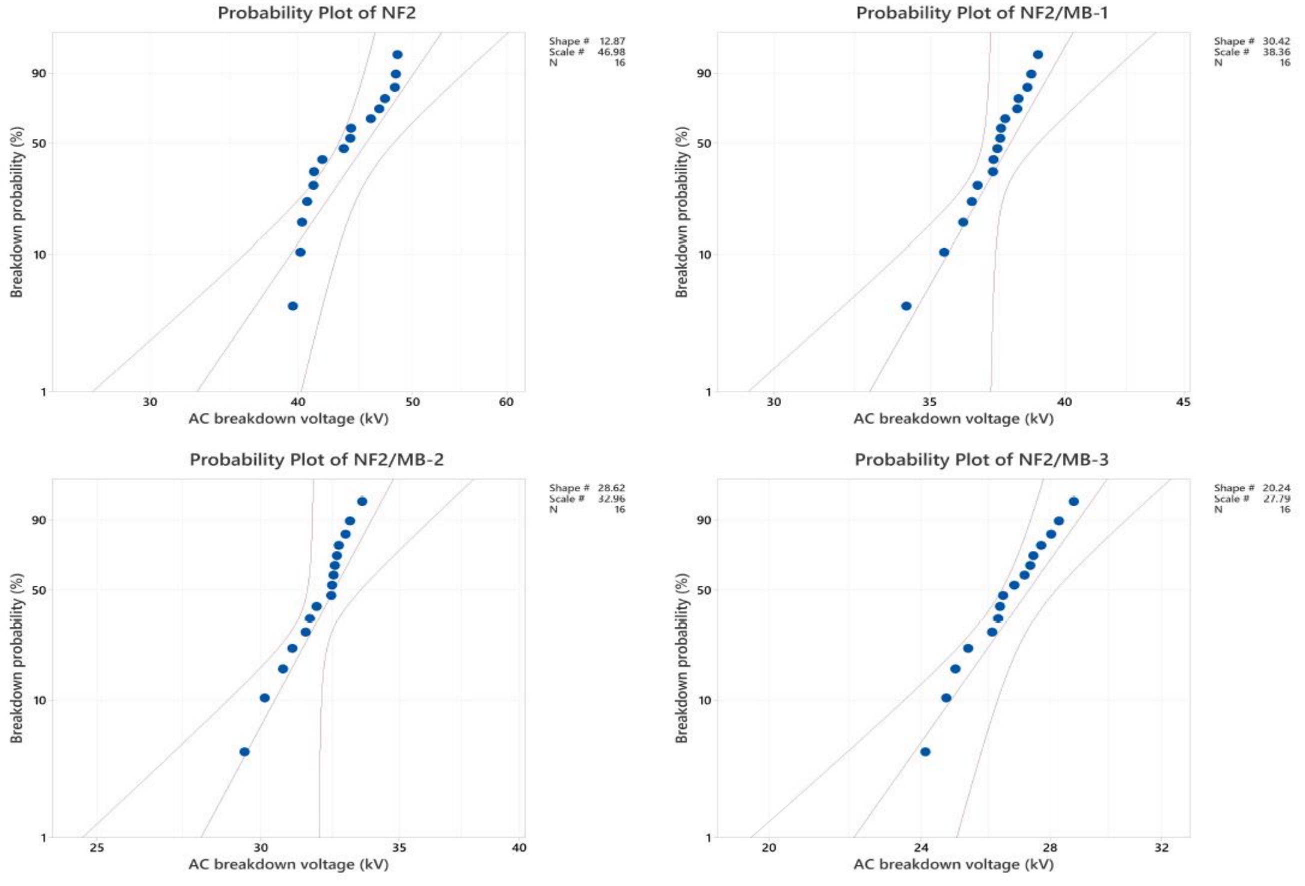

Fig. 9 Weibull plot of AC breakdown voltage : 0.016% Fe_3O_4 Nanofluid (NF2), 0.016% Fe_3O_4 Nanofluid with metal ball 1 mm (NF2/MB-1), 0.016% Fe_3O_4 Nanofluid with metal ball 2 mm (NF2/MB-2), 0.016% Fe_3O_4 Nanofluid with metal ball 3 mm (NF2/MB-3).

The Weibull probability plots offer valuable insights into the distribution of AC breakdown voltage in mineral oil and Fe_3O_4 nanofluids under various contamination scenarios. An understanding of these distributions can assist in the design of more reliable.

Tables II-IV present the probability of the breakdown voltage at 1% and 50%, along with the percentage reduction. The breakdown voltage with a probability of 50% represents the mean value, whereas the breakdown voltage with a probability of 1% serves as an estimated value for the lowest probability of breakdown voltage and as an indicator of the reliability of the nanofluid.

TABLE II. BREAKDOWN PROBABILITY OF MINERAL OIL

Sample	**Probability of Breakdown Voltage (%)**	**Breakdown Voltage (kV)**	**Decrement (%)**
MO	1	23.87	-
	50	30.68	-
MO/MB-1	1	16.99	28.82
	50	22.78	25.75
MO/MB-2	1	13.57	43.15
	50	18.70	39.05
MO/MB-3	1	10.26	57.02
	50	15.42	49.74

TABLE III. BREAKDOWN PROBABILITY OF 0.008% Fe_3O_4 NANOFLUID

Sample	**Probability of Breakdown Voltage (%)**	**Breakdown Voltage (kV)**	**Decrement (%)**
NF1	1	49.11	-
	50	56.34	-
NF1/MB-1	1	37.59	23.46
	50	43.39	22.98
NF1/MB-2	1	34.03	30.71
	50	38.84	31.06
NF1/MB-3	1	28.10	42.78
	50	34.89	38.07

TABLE IV. BREAKDOWN PROBABILITY OF 0.016% Fe_3O_4 NANOFLUID

Sample	**Probability of Breakdown Voltage (%)**	**Breakdown Voltage (kV)**	**Decrement (%)**
NF2	1	32.86	-
	50	45.66	-
NF2/MB-1	1	32.98	0.36
	50	37.90	16.99
NF2/MB-2	1	28.07	14.58
	50	32.54	28.73
NF2/MB-3	1	22.14	32.62
	50	27.29	40.23

C. Levitation voltage test results

The elevated supply voltage prompts the metal particles to be induced by the electric charge, thereby engendering a robust electric field encompassing the metal particles and electrode. This pervasive electric field distribution enables the metal particles to move. The levitation voltage is a condition in which the electrostatic force between the metal particles and the surrounding oil is sufficiently robust to counterbalance the gravitational force acting on the metal particles. In the context of levitation voltage testing, metal particles suspended in oil or nanofluid exhibit a voltage at which they begin to levitate or suspend in the oil.

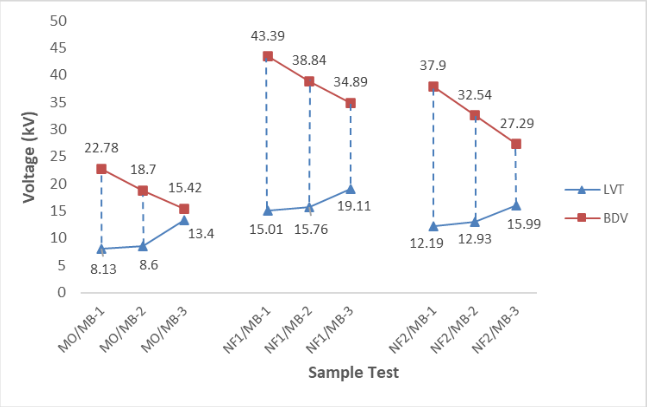

Fig. 10 Levitation and Breakdown voltage of Metal Ball Particle in the insulation fluid

Figure 10 illustrates the values of levitation voltage and breakdown voltage (Weibull Probability 50%) for nine test samples, including mineral oil with contaminants of 1 mm metal ball particle (MO/MB-1), 2 mm metal ball particle (MO/MB-2), 3 mm metal ball particle (MO/MB-3), 0.008% Fe_3O_4 Nanofluid with contaminants of 1 mm metal ball particle (NF1/MB-1), 2 mm metal ball particle (NF1/MB-2), 3 mm metal ball particle (NF1/MB-3), 0.016% Fe_3O_4 Nanofluid with contaminants of 1 mm metal ball particle (NF2/MB-1), 2 mm metal ball particle (NF2/MB-2), and 3 mm metal ball particle (NF2/MB-3). The particles included in the study were as follows: 1 mm metal ball particle (MO/MB-1), 2 mm metal ball particle (MO/MB-2), 3 mm metal ball particle (MO/MB-3), 0.016% Fe_3O_4 Nanofluid with contaminants of 1 mm metal ball particle (NF2/MB-1), 2 mm metal ball particle (NF2/MB-2), 3 mm metal ball particle (NF2/MB-3). The levitation voltage in each insulation fluid sample increased as the size of the ball particle contaminants increased. This indicates that the larger the size of the ball particles, the greater the electric field required to make the ball particles move or float. Meanwhile, the breakdown voltage decreased when the number of ball particles increased. The levitation voltage indicates that the higher the levitation voltage value, the higher is the electric field that occurs, which in turn leads to a faster breakdown. Conversely, a lower levitation voltage results in slower breakdown.

IV. CONCLUSION

This paper presents the results of a study that provides an in-depth understanding of the breakdown voltage characteristics of insulating fluids contaminated by metal particles. The results confirm that contaminant particle size has a significant impact on the breakdown voltage. Larger particles tend to cause a larger drop in the breakdown voltage. This phenomenon indicates the importance of paying attention to particle size in an effort to maintain insulation performance. Second, the experimental analysis indicates that the nanofluid with a concentration of 0.008% Fe_3O_4 exhibits superior breakdown voltage performance to mineral oil and 0.016% Fe_3O_4 nanofluid. Although the concentration of 0.016% Fe_3O_4 also demonstrated enhanced performance compared with mineral oil, the experimental results highlight that the optimal nanoparticle dosage concentration is crucial for preventing breakdown stress. These findings provide important insights into the determination of the optimal nanoparticle dosage for the enhancement of insulation performance. Additionally, the study revealed that an increase in levitation voltage was observed as the size of the contaminant particles increased. This illustrates the potential for the generation of elevated electric fields, which can accelerate the occurrence of insulation damage. Consequently, the control of contamination in transformer oil insulation is of paramount importance to prevent breakdowns that can be detrimental to electrical equipment as a whole. Consequently, the findings of this study not only emphasize the importance of controlling contamination in transformer oil insulation but also highlight the necessity of preparing nanofluids with the appropriate concentration and monitoring contaminant particle size to enhance insulation performance and prevent unintentional damage.

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