Enhancing the Dielectric Strength of Agglomerated Insulation Oil Using Fe_3O_4 Nanoparticles: A Study on Partial Discharge Behavior

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Abstract: - Nanotechnology is currently experiencing rapid development, especially in high-voltage equipment. One of them is a nanofluid as an insulating medium to replace transformer oil, which was developed by mixing nanoparticles with oil. Many studies have developed nanofluids and found that mixed nanoparticles can disperse with oil. The advantages of nanofluids include improved thermal properties, increased dielectric strength, and accelerated cooling of the transformer oil insulation. One type of conductive nanoparticle, Fe_3O_4, has been widely studied and tested with respect to the increase in the breakdown voltage. The breakdown condition of nanofluids does not escape the partial discharge (PD) phenomenon during pre-breakdown conditions. Therefore, in this study, a Fe_3O_4 nanofluid PD detection test was carried out to determine the characteristics of PD. The PD detection test used an electrical method with a measurement circuit (RC circuit) tool and an AC high-voltage generator. Other tests were also carried out with Particle Size Analyzer (PSA) testing to determine the stability of the nanofluids and electrical conductivity tests to determine the conductive value of the nanofluids. Significant nanofluid deposition was observed after being left for 170 hours. Thus, the results of the comparison of the 24 hours and 170 hours PSA nanofluid testing obtained the largest value of 47.8 and the smallest value of 24.76. The results of the electrical conductivity test showed that doses of more than 0.008% nanoparticles Fe_3O_4 caused an increase in the conductivity value. The results of the PD characteristics obtained the average value of the PDIV that was left for 24 hours (14.12 kV - 12.73 kV) and 170 hours (13.45 kV-11.43 kV). The PDIV value is in line with the breakdown voltage value, and its value decreases due to the increase in nanoparticle dosage. Analysis of the PRPD patterns. The PRPD pattern of the average phase shift of the PD point that appears in the positive cycle is in the 8.4°–358° phase, and in the negative cycle at 6.9° - 357.7°. The number of PRPD points on the nanofluid Fe_3O_4 was left for 24 hours more than 170 hours.

Key-Words: - Fe_3O_4, Mineral Oil, Nanoparticle, Partial Discharge, PDIV, PRPD

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1. Introduction

Power transformers play a crucial role in the transmission and distribution networks of electric power systems [1]. During the construction of these transformers, a coil is immersed in transformer oil, which serves as both insulation and cooling agent [2]. Mineral transformer oil is commonly used as a liquid insulating material because of its exceptional dielectric strength, affordability, and potential for transformer cooling [3-4]. However, the continuous operation of transformers for daily power requirements can lead to a decrease in the dielectric strength of oil insulation. To address this issue, scientists have turned to nanotechnology research and transformer oil.proposed the addition of nanoparticles.

Several studies have been conducted to assess the impact of nanoparticle additives on the dielectric and thermal properties of nanofluids. Fe_3O_4 has emerged as a promising nanoparticle for enhancing the dielectric strength. Segal et al. investigated the effects of mixing 10 nm Fe_3O_4 with mineral oil. The results showed that the breakdown voltage of the nanofluid increased by 36.64% compared that with of conventional transformer oil [5]. In another study, the addition of 40 mg of Fe_3O_4 to a nanofluid led to a 48% increase in the breakdown voltage of pure mineral oil [6].

Based on the research conducted, it was found that nanofluids are susceptible to dielectric failure due to insulation damage. The field-strength limits of insulating materials vary depending on the specific material used. If the applied voltage surpasses the insulation capability, it leads to breakdown voltage. Prior to the breakdown voltage, a partial discharge (PD) event occurs within the insulating material [7]. PD refers to a localized electrical discharge that only partially bridges the gap between electrodes or causes a jump in the electrical charge on the insulation due to a potential difference, without completely connecting the two electrodes [8]. Considering nanofluids as insulating materials, PD events certainly occur. Consequently, it is imperative to conduct PD detection research using diverse methods, types of nanoparticles, and transformer oils.

This study focuses on the examination of PD detection in Fe_3O_4 nanofluids composed of a combination of mineral oil and conductive Fe_3O_4 nanoparticles. To perform the PD detection test, an electrical method was employed, utilizing a measurement circuit (RC circuit) detection device that was connected to an oscilloscope. This setup allowed for the determination of PD characteristics. The study also analyzed the discrepancies in the PD nanofluid characteristics after being left for 24 and 170 hours, which were subsequently used to draw conclusions. Additionally, particle size analysis (PSA), breakdown voltage tests, and electrical conductivity tests were conducted on the Fe_3O_4 nanofluids.

1. Experimental Setup

1.1 Preparation of Fe_3O_4 Nanofluids

Mineral oil, Shell Diala ZX4S-1, was used as the liquid insulating material in this investigation.The physical characteristics of this oil are provided in Table 1.

Table 1 Oil Specifications

Properties	Mineral Oil	Unit
Density	805	Kg/m3
Kinematic Viscosity @400C	9.9	mm2/s
Flashpoint	191	^{0}C
Pour Point	-42	^{0}C
Breakdown Voltage Untreated	70	kV

1.2 Preparation of Fe_3O_4 Nanofluids

Five samples were prepared for this investigation, each containing a nanofluid mixture consisting of Fe_3O_4 nanoparticles (Fe) and mineral oil (MO). These samples were prepared with varying concentrations of mixed nanoparticles and two different types of insulating oils. Prior to conducting the experiment, a pre-conditioning step was performed on the insulating oil to remove any solid contaminant particles through filtration [9]. Subsequently, the oil was heated to a temperature of 90 °C in a vacuum oven for 24 hours. Simultaneously, the nanoparticles were dried at 200 °C for 2 hours to reduce the moisture content in the nanoparticle powder, thereby facilitating better mixing with the insulating oil [10]. The mixture of insulating oil and nanoparticles was then stirred for one hour using a magnetic stirrer at 300 RPM. Furthermore, the nanofluids underwent sonication, specifically mechanical stabilization using an ultrasonic cleanser, to enhance their solubility. To determine the electrical properties of each specimen, the nanofluid was allowed to agglomerate for 24 hours and 170 hours, as it was assumed that these durations corresponded to the accumulation process of particle size [11]. Table II presents the variations in nanoparticle concentration with respect to the volume of mineral oil.

Table 2. Nanofluid Variations with Mineral Oil

Fe_3O_4 Nanoparticle	Mineral Oil	Percentage of Fe3O4 Nanoparticle	Mixture Code
0 mg	300 ml	0.000 %	MO
10 mg	300 ml	0.003 %	MO/Fe-1
25 mg	300 ml	0.008 %	MO/Fe-2
50 mg	300 ml	0.016 %	MO/Fe-3
100 mg	300 ml	0.033 %	MO/Fe-4

1.3 Particle Size Analyzer Testing

The Particle Size Analyzer (PSA) method [12] was used to determine the physical characteristics of the particles in the nanofluid samples. The solubility and stability of the nanoparticles were investigated. A Nano Sizer analysis tool was employed for PSA testing. The procedure involved pouring three nanofluid samples, each with a volume of 1.5 ml, into a cuvette. This cuvette was then inserted into the device, which detected the physical properties of the nanofluid sample by analyzing the light effect on the front side and utilizing a sensor on the back side [13]. The tests were conducted for both 24 and 170 hours, allowing examination of the agglomerating nanofluids.

1.4 Electric Conductivity Testing

The resistance of the nanofluid was determined by electrical conductivity testing [14]. To investigate this, the experiment was carried out using three distinct voltage levels (0.25, 0.5, and 1 kV) for every variation of nanofluids that were left to age for durations of 24 and 170 hours, as specified in Table II. The testing procedure entailed the use of a high-voltage insulation tester that applied a DC voltage to the insulating material of the nanofluid.

1.5 Breakdown Voltage Testing

The objective of the Breakdown Voltage (BDV) test is to assess the capacity of electrical insulation materials to endure high-voltage conditions [15]. The BDV represents the voltage level that surpasses the limits of an insulator's capability, as determined through a specific methodology. The primary factor contributing to the deterioration of insulation materials under high-voltage scenarios is the electrical field. Nevertheless, the introduction of nanoparticles into the base material can potentially modify the distribution of electrical fields between the electrodes, thereby enhancing the insulation quality. To investigate this phenomenon, experiments were conducted on five different nanofluid samples with varying concentrations as outlined in Table II, which were then aged for 24 and 170 hours. These tests were performed using an alternating current (AC) voltage with a frequency of 50 Hz, employing a mushroom electrode configuration with a gap distance of 2.5 mm [16].

1.6 Partial Discharge Testing

In this study, the PD testing method employed was an RC Circuit. This circuit comprises a single resistor, resistor capacitor (RC), and a combination of impedances arranged in accordance with IEC 60270 standards [17-18]. The detection instrument utilized was capable of measuring the PD within a frequency range of up to 300 MHz. Moreover, this circuit is proficient in detecting and quantifying the PD of insulating oil, which exhibits a PD frequency spectrum of up to 200 MHz [19]. The PD testing apparatus is shown in Fig. 1.

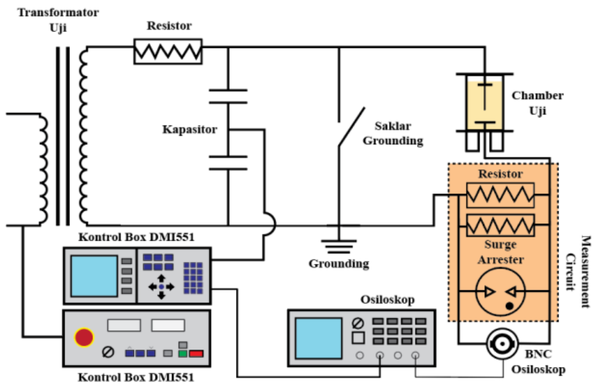

Fig. 1 Partial Discharge Detection Circuit Scheme

2. Result and Data Analysis

2.1 Particle Size Analyzer (PSA) Testing

The Z-average serves as a metric for determining particle size in a solution. A reduction in the Z-average value signifies a decrease in the size of the dispersed particles, suggesting the possibility of agglomeration in the nanofluid. The PSA value of the MO-Fe nanofluid exhibited variations between 24 and 170 hours of deposition, with the Z-average value being smaller after 170 hours of deposition than that after 24 hours of deposition. The data displayed in Table III illustrate the disparity in Z-average values across the largest samples, specifically MO/Fe-1, MO/Fe-2, MO/Fe-3, and MO/Fe-4. The findings indicate that a greater difference in the Z-average corresponds to a reduction in the measurable volume of the nanoparticles. This implies that a larger quantity of nanoparticles was agglomerated.

Despite the decrease in the Z-average value, the Pdi values exhibit a consistent trend, suggesting that the nanofluids remain uniformly mixed. This observation can be attributed to the utilization of a small sample volume (approximately 1.5 ml during PSA testing, which effectively prevents the settled nanoparticles from entering the cuvette. Consequently, the homogeneity of the nanofluid was maintained.

Table 3. Comparison of Agglomerated Nanofluid Test Data for 24 and 170 Hours

Nano fluid	Z Average (d.nm)			Pdi	
	24 Hours	170 Hours	Gap	24 Hours	170 Hours
MO/Fe-1	510.63	462.83	47.80	0.36	0.37
MO/Fe-2	572.00	543.23	28.77	0.32	0.21
MO/Fe-3	631.60	605.30	26.30	0.32	0.32
MO/Fe-4	655.93	631.17	24.76	0.41	0.25

2.2 Electric Conductivity Testing

The dissimilarities in the conductivity measurements between the nanofluid samples after 24 hours and 170 hours of agglomeration can be ascribed to the precipitation of numerous Fe_3O_4 nanoparticles. This precipitation event led to an increase in the overall conductivity of the nanofluids. Upon analyzing the conductivity values presented in Table IV, a consistent pattern was observed. The values, arranged in ascending order, correspond to the concentration of Fe_3O_4 nanoparticles and duration of agglomeration in the nanofluid. It is important to note that mineral oil is employed as the base fluid in this investigation. Additionally, the Fe_3O_4 nanofluid deposited for 24 and 170 hours, exhibits varying conductivity values across the MO/Fe-1, MO/Fe-2, MO/Fe-3, and MO/Fe-4 samples. Hence, it can be deduced that as the quantity of Fe_3O_4 nanoparticles in the nanofluid increased, the settling of more conductive nanoparticles resulted in an increase in the conductivity value.

Table 4. Comparison of Conductivity Values of Nanofluid (Mineral Oil) Precipitated for 24 and 170 Hours

Nanofluid	Conductivity (aS/mm)		
	24 hours	170 hours	Gap
MO/Fe-1	52.90	56.00	3.10
MO/Fe-2	58.50	62.15	3.65
MO/Fe-3	69.30	76.15	6.85
MO/Fe-4	71.80	81.62	9.88

2.3 Breakdown Voltage Testing

According to Table V, the breakdown voltage of the Fe_3O_4 nanofluid surpassed that of mineral oil. This disparity can be attributed to the presence of conductive nanoparticles, which expedite heat transfer and subsequently enhance the breakdown voltage. As the Fe_3O_4 nanoparticle content increased, the breakdown voltage increased at a faster rate, resulting in a decrease in its value. Additionally, the duration of agglomeration influences the breakdown voltage, as evidenced by the lower breakdown voltage value observed in the nanofluid deposited for 170 hours compared to that deposited for 24 hours. This discrepancy can be attributed to the accumulation of sediment in the sample agglomerated for 170 hours. After conducting the tests, the average breakdown voltage of the nanofluid was determined to be 22.83 kV after 24 hours of settling and 21 kV after 170 hours.

Table 5. Breakdown Voltage Value of Nanofluids Variation

Nanofluid	Breakdown Voltage (kV)	
	24 Hours	170 Hours
MO	19,76	19,7
MO/Fe-1	23,42	21,83
MO/Fe-2	24,12	22,51
MO/Fe-3	23,54	20,39
MO/Fe-4	23,33	20,59
Average	22.83	21.00

2.4 Partial Discharge Testing

Consequently, the maximum limit of the voltage generated in the test was established as 19 kV, which corresponds to 80% of the average breakdown voltage [18].

3.4.1 Partial Discharge Inception Voltage (PDIV) Testing

The objective of testing nanofluids Fe_3O_4 through partial discharge inception voltage (PDIV) is to determine the initial voltage at which partial discharge (PD) occurs. This test was conducted under pre-breakdown conditions, which are indicated by impulses of varying amplitudes. PDIV in liquid insulation, particularly in nanofluids, is highly susceptible to change, making the observation process challenging. To determine the PDIV, an electrical method is employed, which involves using a measurement circuit (RC circuit) detection device connected to an oscilloscope. The test utilizes a chamber and needle to create test electrodes, which serve as the test media. A series of PDIV tests was performed in accordance with the IEC 60343 standard.

PDIV testing was conducted five times, specifically referred to as P-1, P-2, P-3, P-4, and P-5. Subsequently, the average PDIV was determined based on the results obtained from five experiments. Each experiment involved administering nanofluid samples of Fe_3O_4 at varying doses of 0%, 0.003%, 0.008%, 0.016%, and 0.033%. These five nanofluid samples were then subjected to two different conditions: one where they were allowed to stand for 24 hours, and another where they were allowed to stand for 170 hours.

Tabel 6 PDIV Results Nanofluid of Fe_3O_4 Settled for 24 hours.

Nanofluid Code	Doses (%)	PDIV Testing (kV)					BDV Average (kV)
		P-1	P-2	**P-3**	**P-4**	**P-5**	P-2
MO/Fe-0	**cc**	**13,54**	**13,47**	**13,55**	**13,63**	**16,40**	13,47
MO/Fe-1	**0.003**	**13,76**	**13,52**	**14,58**	**14,45**	**14,77**	13,52
MO/Fe-2	**0.008**	**14,32**	**14,70**	**15,43**	**14,40**	**15,37**	14,70
MO/Fe-3	**0.016**	**13,55**	**13,52**	**13,40**	**13,55**	**13,78**	13,52

Tabel 7 PDIV Results Nanofluid of Fe_3O_4 Settled for 170 hours.

Nanofluid Code	Doses (%)	PDIV Testing (kV)					BDV Average (kV)
		P-1	P-2	**P-3**	**P-4**	**P-5**	P-2
MO/Fe-0	**0**	**13,55**	**13,20**	**13,55**	**13,56**	**13,37**	**13,45**
MO/Fe-1	**0,003**	**13,45**	**13,14**	**14,47**	**13,48**	**14,42**	**13,79**
MO/Fe-2	**0,008**	**14,17**	**14,59**	**14,81**	**14,37**	**14,76**	**14,54**
MO/Fe-3	**0,016**	**12,56**	**12,95**	**12,31**	**12,74**	**13,36**	**12,78**

Tables 6 and 7 present the PDIV data for the five nanofluid samples of Fe_3O_4 after 24 and 170 hours of standing, respectively. The average PDIV value was calculated based on the results of the five experiments. The data indicate that an increase in the dose of 0.008% nanoparticles in the MO/Fe-2 nanofluid led to a decrease in both the average PDIV and breakdown voltage values. Furthermore, nanofluids left to stand for 170 hours exhibited a lower average PDIV than those left for 24 hours, due to the extended deposition time. The average PDIV value at a voltage of 16 kV was used for PRPD data collection.

3.4.2 Phase Resolved Partial Discharge (PRPD) Testing

Phase-resolved partial discharge (PRPD) testing is a method used to measure and capture PD signals at different voltage phase cycles under pre-breakdown conditions. The analysis of PRPD results in point patterns indicate the quantity of PD occurrences. Additional data obtained from PRPD include the PD magnitude, phase angle of PD occurrences, and PD distribution.

In the PRPD analysis, five nanofluid samples with varying concentrations (0%, 0.003%, 0.008%, 0.016%, and 0.033%) were used. The PRPD conditions were examined under different voltage levels of 16 kV and 19 kV. The selection of 16 kV is close to the average PD inception voltage (PDIV), whereas 19 kV is close to the average breakdown voltage. Data were collected 30 times to achieve an optimal PD distribution pattern observed from the initial and final phases of PD occurrence. The PD detection test used an electrical method with a measurement circuit (RC circuit). The specifications of the models are listed in Table 8.

Table 8. Test model specifications.

	Model
BNC Female	2 Pin Terminal
Resistor	50 Ω
Arrester	150 kV
Banana Socket Female	15 × 16 mm

Based on the experiments that were conducted based on the voltage level, nanoparticle concentration, and dissolution time, it can be seen that each magnitude distribution at each concentration variation is presented in the pictures below.

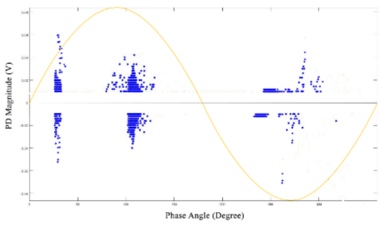

Fig. 2 PRPD MO/Fe-0 to stand for 24 hours at a voltage of 16 kV

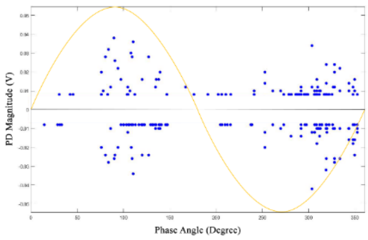

Fig. 3 PRPD MO/Fe-1 to stand for 24 hours at a voltage of 16 kV

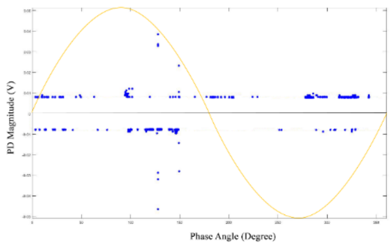

Fig. 4 PRPD MO/Fe-2 to stand for 24 hours at a voltage of 16 kV

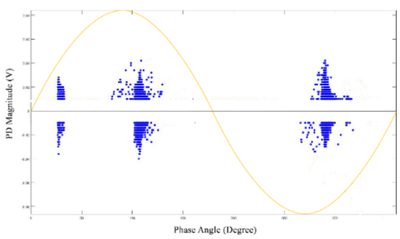

Fig. 5 PRPD MO/Fe-3 to stand for 24 hours at a voltage of 16 kV

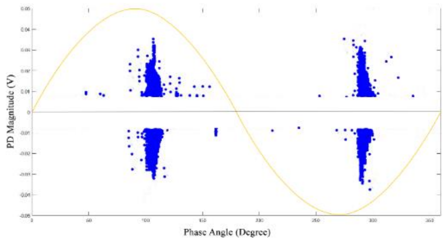

Fig. 6 PRPD MO/Fe-4 to stand for 24 hours at a voltage of 16 kV

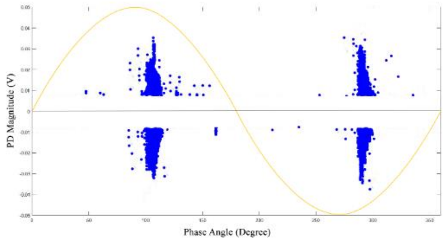

Fig. 7 PRPD MO/Fe-0 to stand for 24 hours at a voltage of 19 kV

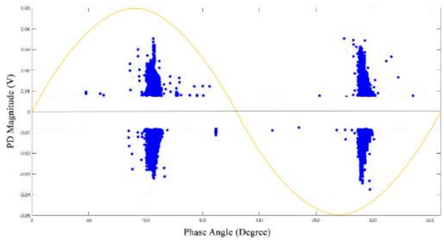

Fig. 8 PRPD MO/Fe-1 to stand for 24 hours at a voltage of 19 kV

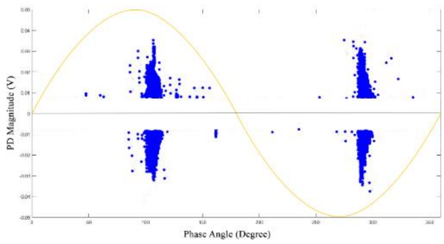

Fig. 9 PRPD MO/Fe-2 to stand for 24 hours at a voltage of 19 kV

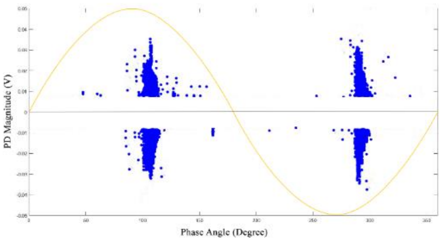

Fig. 10 PRPD MO/Fe-3 to stand for 24 hours at a voltage of 19 kV

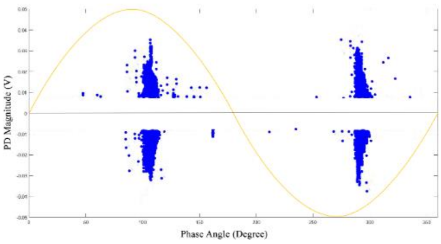

Fig. 11 PRPD MO/Fe-4 to stand for 24 hours at a voltage of 19 kV

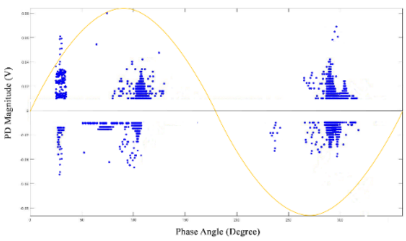

Fig. 12 PRPD MO/Fe-0 to stand for 170 hours at a voltage of 16 kV

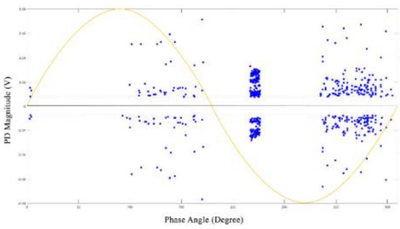

Fig. 13 PRPD MO/Fe-1 to stand for 170 hours at a voltage of 16 kV

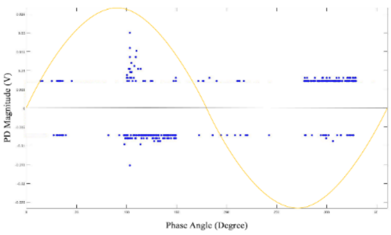

Fig. 14 PRPD MO/Fe-2 to stand for 170 hours at a voltage of 16 kV

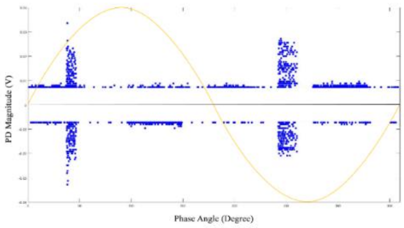

Fig. 15 PRPD MO/Fe-3 to stand for 170 hours at a voltage of 16 kV

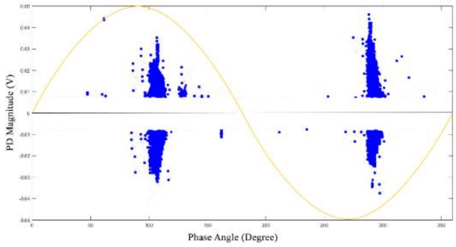

Fig. 16 PRPD MO/Fe-4 to stand for 170 hours at a voltage of 16 kV

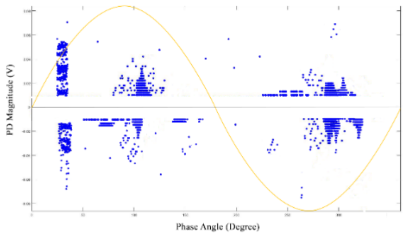

Fig. 17 PRPD MO/Fe-0 to stand for 170 hours at a voltage of 19 kV

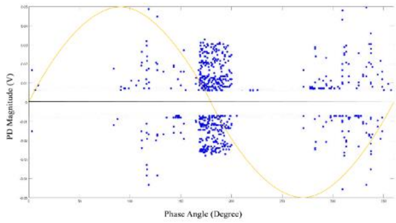

Fig. 18 PRPD MO/Fe-1 to stand for 170 hours at a voltage of 19 kV

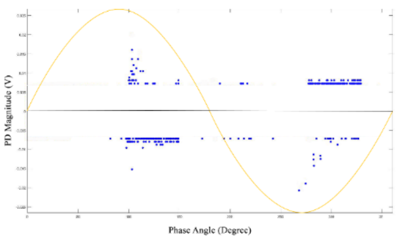

Fig. 19 PRPD MO/Fe-2 to stand for 170 hours at a voltage of 19 kV

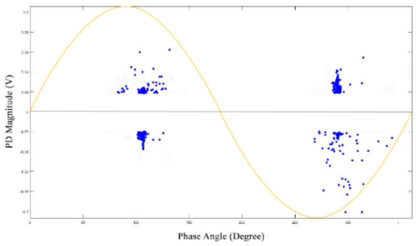

Fig. 20 PRPD MO/Fe-3 to stand for 170 hours at a voltage of 19 kV

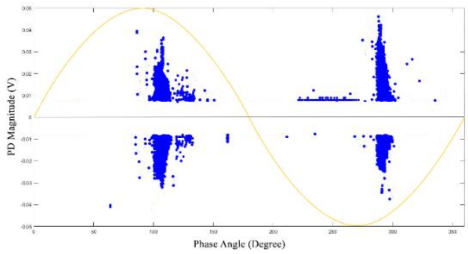

Fig. 21 PRPD MO/Fe-4 to stand for 170 hours at a voltage of 19 kV

All the figures above show the PD distribution at its magnitude and phase. Figure 2 until figure 6 shows that at a voltage level of 16 kV and settled for 24 hours, MO/Fe-4 was obtained, which had the highest number of partial discharge points. Figure 7 until figure 11 shows that at a voltage level of 19 kV and settled for 24 hours, MO/Fe-4 was obtained, which had the highest number of partial discharge points. Figure 12 until figure 16 shows that at a voltage level of 16 kV and settled for 170 hours, MO/Fe-3 was obtained, which had the highest number of partial discharge points. Figure 17 until figure 21 shows that at a voltage level of 19 kV and settled for 170 hours, MO/Fe-3 was obtained, which had the highest number of partial discharge points. If we sum every PD point based on time. If we sum up the pd points based on time, the nanofluid is allowed to stand, Mo/Fe-4 is the nanofluid variation with the most PD points when it is allowed to stand for 24 hours while Mo/Fe-3 is the nanofluid variation with the most pd points when allowed to stand for 170 hours. Furthermore, we can see the total distribution of the PD points in Table 9.

Table 9. Number of PD Points of Nanofluid Fe_3O_4 Settled for 24 Hours and 170 Hours.

z	Voltage	MO/Fe-0	MO/Fe-1	MO/Fe-2	MO/Fe-3	MO/Fe-4
24 hours	16 kV	688	715	215	1156	1196
	19 kV	625	750	234	1269	1322
Total		1313	1465	449	2425	2518
170 hours	16 kV	614	607	76	1210	659
	19 kV	626	624	107	1108	732
Total		1240	1231	183	2318	1391
Average Value		1276	1348	316	316	1954.5

In addition, we can also determine the respective peak amplitudes in each of the PRPD's graphs above. For example. Table 9 shows that the nanofluid Fe_3O_4 MO/Fe-4 was allowed to stand for 24 hours at a voltage of 16 kV, and the highest magnitude recorded was 0.042 V at a phase of 290.8° in the positive cycle, and the lowest magnitude recorded was − 0.042 V at a phase of 101° in the negative cycle. The PRPD pattern of MO/Fe-4 revealed that PD occurrences spread across the positive cycle from phase 49.5° to 346.8°, whereas in the negative cycle, PD occurrences were observed from phase 87.2° to 303.4°. In the nanofluid, Fe_3O_4 was allowed to stand for 170 hours at a voltage of 16 kV; MO/Fe-4 had the highest magnitude recorded at 0.056 V at a phase of 292.6° in the positive cycle, and the lowest recorded magnitude was − -0.048 V at a phase of 294.8° in the negative cycle. The PRPD pattern of MO/Fe-4 indicates that PD occurrences spread across the positive cycle from phase 49.2° to 345.2°, whereas in the negative cycle, PD occurrences are observed from phase 87.3° to 302°, as shown in Figure 3.

PRPD testing was also carried out at a voltage of 19 kV, which corresponds to an average voltage close to the breakdown voltage. Nanofluid Fe_3O_4 was allowed to stand for 24 hours and 170 hours at a voltage of 19 kV. At a voltage of 19 kV, MO/Fe-4 was obtained, which had the highest number of partial discharge points. Figure 4 shows that in MO/Fe-4 stands for 24 hours, the highest magnitude recorded was 0.042 V at a phase of 106.3° in the positive cycle, and the lowest magnitude recorded was − -0.092 V at a phase of 282.4° in the negative cycle. The PRPD pattern of MO/Fe-4 indicates that PD occurrences spread across the positive cycle from phase 22.1° to 347°, whereas in the negative cycle, PD occurrences were observed from phase 21.7° to 350.5°. Nanofluid Fe_3O_4 was allowed to stand for 170 hours at a voltage of 19 kV. In MO/Fe-4, the highest magnitude recorded was 0.048 V at a phase of 105.4° in the positive cycle, while the highest magnitude recorded was 0.087 V at a phase of 283° in the negative cycle. The PRPD pattern of MO/Fe-4 revealed that PD occurrences are distributed in the positive cycle from a phase of 84.9° to 300.1°, and in the negative cycle, from a phase of 72.5° to 317.5° as shown in Fig. 5.

Table 10. PRPD Nanofluid Phase-Shift Fe_3O_4 Settled for 24 Hours.

Position	Voltage	Mo/ Fe-0	Mo/ Fe-1	Mo/ Fe-2	Mo/ Fe-3	Mo/ Fe-4
Positive Cycle	16 kV	25,2°-309,4°	38,1°-355°	21,6°-348,2°	26,4°-348°	49,5°-346,8°
	19 kV	25,2°-300,9°	8,6°-326°	76,4°-322,4°	25,2°-349,2°	22,1°-347°
Negative Cycle	16 kV	24,8°-330°	18,3°-354,5°	16,8°-348°	26°-327,2°	87,2°-303,4°
	19 kV	26°-328,5°	9,1°-336,5°	102°-347,7°	25,4°-350,5°	21,7°-350,5°

Table 11. PRPD Nanofluid Phase-Shift Fe_3O_4 Settled for 170 Hours.

Position	Voltage	Mo/ Fe-0	Mo/ Fe-1	Mo/ Fe-2	Mo/ Fe-3	Mo/ Fe-4
Positive Cycle	16 kV	26,6°-327,2°	8,4°-355,5°	18,6°-326,4°	2,4°-358°	49,2°-345,2°
	19 kV	25,4°-326,5°	10,3°-357,7°	101,5°-337,5°	8,5°-349,3°	84,9°-300,1°
Negative Cycle	16 kV	27°-331,6°	6,9°-354,3°	25°-318,1°	26°-327,2°	87,3°-302°
	19 kV	26°-328,5°	11°-348,2°	87,1°-326,9°	9°-328°	72,5°-317,5°

Then, we know that the magnitude values in the PRPD patterns of all Fe_3O_4 nanofluid samples will increase with increasing voltage, and analysis indicates that the voltage increment does not affect phase shift.

3. Conclusion

After processing the data from nanofluid of Fe_3O_4testing. The following conclusions were drawn.

1. The nanofluid of Fe_3O_4 is a solution in which the nanoparticles are evenly mixed and little precipitation was observed. However, after 170 h, the nanofluid experienced significant precipitation.
2. PSA testing was conducted on nanofluids of Fe_3O_4, allowing them to stand for 24 hours and 170 hours. The analysis revealed notable differences in the Z-average and PDI data. Among the tested samples, the order of the data with the largest Z-average difference was MO/Fe-1, MO/Fe-2, MO/Fe-3, and MO/Fe-4. The largest Z-average difference recorded was 47.8 d.nm, whereas the smallest difference was 24.76 d.nm. The magnitude of the Z-average difference served as an indicator of the number of precipitated nanoparticles. Additionally, the Pdi values obtained from the PSA test varied, although they remained below 1. This suggested that the solution was uniformly mixed to ensure homogeneity.
3. The nanofluid of Fe_3O_4 underwent electrical conductivity testing after being left undisturbed for 24 hours and 170 hours. The test revealed the electrical conductivity values in descending order as follows: MO/Fe-4, MO/Fe-3, MO/Fe-2, MO/Fe-1, and MO/Fe-0, with the highest value recorded as 0.0000098 pS/mm and the lowest as 0.0000031 pS/mm. Consequently, the presence of nanoparticles in the “Fe3O4” nanofluid significantly influenced its electrical conductivity.
4. Nanofluid of Fe_3O_4 is conductive so that it can increase the breakdown voltage value and is good at conducting heat in transformer liquid insulation. The breakdown voltage of MO/Fe-1 was greater than that of MO/Fe-0 (mineral oil). However, nanofluids with a dose of more than 0.008% decrease the breakdown voltage because nanoparticles are conductive.

5. The PDIV average value of Fe_3O_4 nanofluid, after being aged for 24 hours, falls within the range of 14.12 kV to 12.73 kV. However, when the same nanofluid is aged for 170 hours, the PDIV average value decreases and falls within the range of 13.45 kV to 11.43 kV. The decrease in breakdown voltage value is caused by the increase in nanoparticle dosage of Fe_3O_4 more than 0.008%.
6. The magnitude of the PRPD pattern increased when the voltage increased, and the increase in voltage did not affect the phase shift.
7. The typical PRPD pattern of the PD phasic shift occurring during the positive cycle is situated between phase angles of 8.4° and 358°, while during the negative cycle, it is positioned between phase angles of 6.9° and 357.7°. It was observed that the quantity of PRPD points was higher in the nanofluid denoted as "Fe_3O_4" aged for 24 hours in the same nanofluid aged for 170 hours.

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