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Research Article

An Investigation of the Electrical Properties of Pressboard Impregnated with Mineral Oil-Based Nanofluids at Different Concentrations of Fe_3O_4 Magnetic Nanoparticles

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The purpose of this study was to investigate the electrical properties of pressboard impregnated with mineral oil-based nanomaterial. The nanomaterial focused on in this study was magnetite (Fe_3O_4) at ratios of 0.01%, 0.03%, and 0.05% by mineral oil volume. The electrical tests were performed on the AC breakdown strengths and positive-negative lightning impulse breakdown strengths on impregnated pressboard were carried out in compliance with IEC 60641 and IEC 60243, respectively. Scanning electron microscopy (SEM) and X-ray Diffraction (X-RD) were used to study the micro surface and show that Fe_3O_4 nanoparticles of nanoscale size were adhered to the pressboard surface and exist in an amorphous state. The results found that the AC breakdown strengths of pressboard impregnated with mineral oil-based Fe_3O_4 nanofluids at 0.03 wt% were increased the most. Moreover, the lightning impulse breakdown strengths of pressboard impregnated with mineral oil-based Fe_3O_4 nanofluids at 0.03 wt% were increased the most in both positive and negative polarities. The results, thus, showed promising directions for applications of Fe_3O_4 nanomaterials to improve the electrical properties of pressboard.

1. Introduction

Transformers are an essential instrument in an electrical power system, which serve to increase or decrease voltages based on objectives consistent with purposes of usage. They consist of two types of insulators: (1) an oil-immersed insulator dissipates the ongoing heat and restrains currents from flowing from one point to another; (2) insulating pressboard prevents currents from flowing between coils as a divider and dissipates the heat as well. Pressboard is a multilayered cellulose-based material constructed into a hard material and is used in concert with mineral oil or transformer oil in transformers. The frequent usage often causes deterioration, as the heat, the humidity, the acidity, and deterioration of pressboard undoubtedly affect the life of transformers [1–4]. In 2014 [5], LIU Heqian et al. presented a paper about analysis of the dielectric and breakdown characteristics of Nano MMT modified insulation pressboard. Their paper analyzed the dielectric and breakdown properties of nano-MMT modified pressboard at ratios of 0%, 1%, 2.5%, 5%, and 7.5%. The relative permittivity of modified pressboard is not significantly affected by the intensity of the electric field. As the ratio of nanodoping is increased, the relative permittivity of modified pressboard exhibits a tendency to initially decline and then progressively rise. It falls off to its lowest level at a nanodoping ratio of 1%, which is 14% less than unmodified ones. This is due to the Montmorillonite (MMT) particles' ability to spread through

the cardboard following stripping as nanoscale lamella. The MMT layer restricts and makes it challenging to flip the polar groups in pressboard fibers, which lowers the dielectric constant. Space charges are easily attracted to the interface between MMT layers and fibers when the nano doping ratio rises because MMT layers have a greater specific surface area. As a result, interfacial polarization raises the composite's dielectric constant [5, 6]. In 2018 [7], Chao Wei et al. also conducted a study about the effect of nano Al_2O_3 doping modification on the AC/DC superimposed breakdown characteristics of insulating paper; the study investigated the electrical properties of mineral oil-impregnated pressboard impregnated with Al_2O_3 nanoparticle-based mineral at a 2% ratio by weight of insulating oil. The results showed that the dielectric constant of the Al_2O_3-based pressboard declined from 3.23 to 3.03 while the dielectric loss decreased from 0.021 to 0.013 by 38.10% when tested at 25°C. When tested at 25–80°C, the nanoparticle-based pressboard possessed a higher breakdown strength than that of the conventional insulating oil-based pressboard [7–10]. Many studies have been conducted on the effect of nanoparticles on the dielectric properties of mineral oil [11–16], including the size of Fe_3O_4 nanoparticles that generate the various insulation performances of nanofluid impregnated paper, as studied in Ref. [17]. The development and optical characteristics of nanosystems based on polyvinyl alcohol and tri sodium citrate as capping agents for ferromagnetic nanosize particles of iron oxide Fe_2O_3 are examined by Mohammed et al. in Ref. [18], along with the absorption region and direct and indirect energy gap structure. According to the test results, nanocomposites exhibit an absorption peak with a distinctive wavelength between 450 and 500 nm. Peak location was found to have changed significantly. The band gaps were found to range from 1.77 to 2.25 eV. The nanoparticles were well-capped with capping agents, according to the Fourier transformation infrared data. Sharapaev et al. in this paper [19] stated that densely packed opal-like structures were used to synthesize ε-Fe_2O_3 template structures. The matrix properties and heat treatment settings have an impact on iron oxide crystallization as well as the structure and phase composition of iron (III) oxide nanopowders. Fe_2O_3 nanoparticles were synthesized via template synthesis in the pores of matrices that resembled opals. Calcination at a temperature of 1000 °C for 2–4 hours is the best method for producing ε-Fe2O3nanoparticles in opal-like matrices. In mixes of iron oxide modifications, the percentage of ε-Fe2O3 fluctuates from 80–90%. The findings enable the phase composition of the nanopowders produced by this method to be predicted, and they may be used to develop nanostructured materials based on ε-Fe_2O_3, including those that mimic opal. Luo et al. in this paper [20] studies aiming at the layer arrangement in a three-layer absorber based on $Bi_{0.5}Nd_{0.5}FeO_3$ nanocomposite as magneto-electric (M), polybenzazole (D), mixed *M* and *D* samples, and combinations of three-layer samples (layers *M*, D, and D/M) are implemented and evaluated for improved microwave absorption. The constituent characteristics of the research sample, such as $\varepsilon r'$, $\varepsilon r''$, $\mu r'$, and $\mu r''$, are crucial in understanding the effectiveness of the sample as absorbers and shields. Overall, the research samples' total thickness, *d*, ranges from 1.8 to 5 mm and is suitable for use as an absorber for frequencies between 5 and 17 GHz.

The current effort, according to Daniel et al. in 2021 [21], is to investigate the influence of nanoparticles on the dielectric response of cellulose or paper insulation when it is impregnated with an Fe_3O_4-based nanodielectric fluid. As the concentration of nanoparticles rises, the relative permittivity of the oil, or permittivity, increases continuously. When nanoparticle concentrations are low, the permittivity of paper increases, but as the concentration of nanoparticles grows, the permittivity decreases. Furthermore, Wei Yao et al. [22] investigated the impact of Fe_3O_4 nanoparticles with a mass fraction of 0.01 wt% on the propagation and dissipation phases of pre-breakdown in vegetable oil-impregnated pressboard using a 25 mm insulating gap and lightning impulse voltage. According to the results, the Fe_3O_4 magnetic nanoparticles shortened the length of the secondary reverse streamer. Furthermore, nanoparticles have successfully altered the electric field distribution, resulting in the reduction of streamers focused on the parallel direction of the pressboard and an increase in the lightning impulse breakdown voltage.

Nanoparticles can be applied to improve the electrical properties of pressboard. Thus, the present study sought to investigate the electrical properties of pressboard impregnated with mineral oil-based nanofluids at different concentrations of Fe_3O_4 magnetic nanoparticles. The pressboard used in this study was 1.6 mm in thickness, which is commonly used in transformers, while Fe_3O_4 magnetic nanoparticles under 50 nm at different concentrations of 0.01 wt%, 0.03 wt%, and 0.05 wt% ratios by mineral oil volume were used. Such nanoparticles at each ratio were added to the pressboard. Afterwards, pressboard impregnated with mineral oil-based nanofluids was tested to compare its electrical properties with those of the pressboard impregnated with conventional mineral oil. The results were hoped to provide a contribution to enhancing the quality of pressboard impregnated with mineral oil-based nanofluids.

2. Materials and Methods

2.1. Mineral Oil. Mineral oil serves as an insulator and helps dissipate the heat of coils in transformers. Its properties are intertwined with those of diesel fuel and a lubricant. It is produced through the distillation of crude oil, which comprises diverse classes of hydrocarbons divided into three classes based on molecular structures, namely, paraffinic, naphthenic, and aromatic. Paraffinic and naphthenic are stable since they are saturated hydrocarbons, whereas aromatics lack that, considering their unsaturated hydrocarbon state. Each of them features molecules of varying sizes and structural complexities. In fact, tiny hydrocarbons with simple structures are in a gaseous state at room temperature, while those with high molecular mass, fixed complex structures, and high viscosity, e.g., paraffin wax and asphaltic bitumen, are in a solid state at room temperature [23]. Mineral oil commonly used in high-voltage devices may be named differently depending on its properties and usage. For

instance, mineral oil functions as an insulator and dissipates the heat in a power transformer. Even if capacitor oil shares the same properties as mineral oil, it possesses high purity. Thus, it can be used as a medium for impregnating insulators and polymer films for capacitor creation. Among those classes, naphthenic mineral oil from APAR Company in India (POWEROIL TO 20 X) was used in this study. The requirements and terms for testing the properties of mineral oil that passes the testing standards are detailed in Table 1 [24]. It has insulating properties and dissipates the heat efficiently. In addition, it is regarded as normal-grade mineral oil and suitable for a distribution transformer.

2.2. Insulation Pressboard. In addition to being an insulation material, pressboard serves to bear mechanical load resulting from the weight of structures or dynamic load caused by electric currents. Based on chemical structures, it can be classified into different compounds, e.g., organic, inorganic, and polymer. Pressboard is a multilayered cellulose material made of papers compressed by pressure and heat. It is constructed into a hard material with high density. In fact, pressboard is an organic polymer with electrical and mechanical properties, for cellulose is an organic fiber which is stacked and forms porosity, thereby being sensitive to humidity and temperature [25, 26]. Currently, there are various sizes of pressboard in a transformer. Still, in designing a transformer, pressboard is mostly chosen considering thickness by electric power and weight of iron core and coils of a transformer. Insulation pressboard from India's Umang Boards Limited Company was utilized in this investigation. The pressboard provided by the manufacturer has been tested to specification based on the IEC 60641–3.1 : 2008 (certificate No. TC-6778) pre-compressed pressboard from slitted sheets (2000 × 1000) mm, Grade: UB-HD-3.1. The pressboard used in this research, 80 mm × 80 mm in size and 1.6 mm in thickness, was chosen and detailed in Table 2 [27].

2.3. Nanomaterials. Nanomaterials or nanoparticles are synthetic materials formed by atomic or molecular sequencing in the range of 1–100 nanometers in size (1 nanometer corresponds to one billionth of a meter or one-ten thousandth of the diameter of human hair). Their properties and behavior, e.g., conductivity, mechanical properties, and electromagnetic properties, are unlike those of the same class of materials when they are enlarged. Interestingly, because they are created through precise atomic or molecular sequencing, nanomaterials are thought to be perfectly structured and efficient with smaller sizes of materials that can increase the volume of atoms along the surface and interface of materials [28]. In fact, their increasing volume along the interface will directly affect the chemical and physical properties of materials, thus promoting their electrical, electromagnetic, and optical properties, which are completely different from those of large materials [29].

These peculiar properties embedded in nanomaterials enable the development of materials with novel or undiscovered properties. The characteristics of the nanoparticles utilized in this investigation are listed in Table 3 [30].

In this study, magnetite or magnetic oxide (Fe_3O_4) with a diameter of less than 50 nanometers was used in the experiment. Moreover, scanning electron microscopy (SEM) methods were used to determine the size and structure of the dry nanopowder, as shown in Figure 1. The data show that the particle sizes were less than 50 nanometers. The size distribution of Fe_3O_4 nanoparticles was measured by TESCAN, Model: MIRA3.

2.4. Surfactant. Surface active agents are scientifically referred to as surfactants. They are mostly organic compounds that comprise hydrophilic and hydrophobic groups; the latter is usually a hydrocarbon compound primarily composed of hydrocarbon and hydrogen substances mostly derived from fat, natural oil, petroleum, and synthetic polymers. As regards the essential characteristics of surfactants, when a small number of surfactants is added to

Table 1: Specification of mineral oil used for impregnated pressboard.

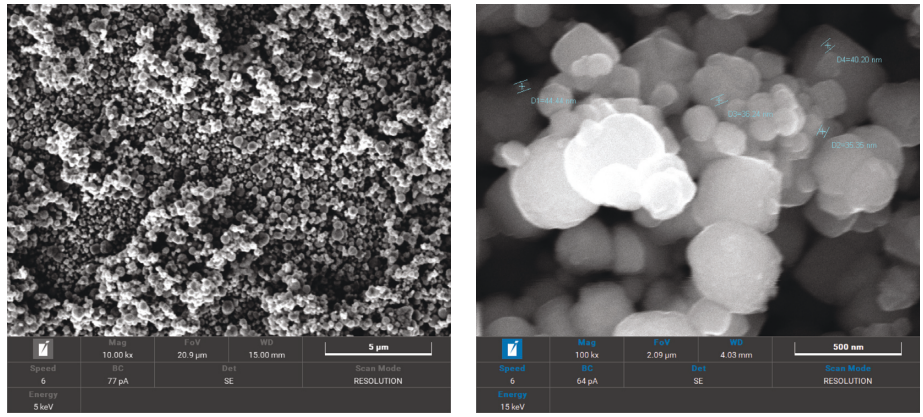
Characteristics	Specification	Test Method
Kinematic viscosity	16.5 mm2/sec (at 40°C)	ISO: 3104
Flash point, PMCC	140°C	ISO: 2719
Pour point	−30°C	ISO: 3016
Density	0.895 g/ml (at 20°C)	ISO: 3675
Interfacial tension	0.04 N/m (at 25°C)	ISO: 6275
Acidity	0.03 mg KOH/g	IEC: 296
Tan δ	0.005 (at 90°C)	IEC: 247

Table 2: Basic parameters of the pressboard used in the present analysis.

Parameters	Specification	Unit
Thickness	1.6 ± 7.5%	mm
Apparent density	1.00–1.20	g/cm^3
Tensile strength-machine direction (MD)	100	MPa
Tensile strength-cross machine direction (CMD)	75	MPa
Moisture content	6	%
Conductivity	5	mS/m
Ash content	0.7	%

Table 3: General characteristics of the Fe_3O_4 nanomaterial type used for pressboard impregnation.

Characteristics	Specification
Parameters	Magnetite (Fe_3O_4)
Average particle size	50 nm
Purity	99.9%
Specific surface area	32 m^2/g
Structure	spinel crystal
Colour	black magnetic powder
Density	0.77 g/cm^3



(a) (b)

FIGURE 1: SEM photographs of Fe_3O_4 nanoparticles. (a) SEM image of the Fe_3O_4 nano powders with 10 kX magnification. (b) SEM image of the Fe_3O_4 nano powders with 100 kX magnification.

water, they reduce the surface tension of water, allowing any process to activate easily. The usage of nanofluids in power transformers is well-known in the literature. Several researchers have already studied the performance of nanoparticles in dielectric fluids, including the fact that there are various types of nanoparticle applications. Besides, surfactants are the stabilizing agents that are utilized for the correct distribution of nanoparticles into the solution to reduce the settling and coagulation of nanoparticles mixed with oil, which may or may not be introduced to the liquid. Nevertheless, there are no regulations or standards regarding the use of surfactants in combination with nanofluids. As a result, the majority of the research is done to determine the appropriate value. For example, the research in Reference [31] by Neera et al. investigated the application of fe_3O_4 nanoparticles to transformer oil and the application of surfactant oleic acid at a 1 mL/1 g (nano) ratio and was used to test the electrical properties. Moreover, many studies have used surfactants of the same type and quantity mixed with many types of nanoparticles, as in the research paper [32]. Hocine et al., studying the influence of conducting (Fe_3O_4), semiconductive (ZnO), and insulating (ZrO_2, SiO_2, and Al_2O_3) nanoparticles at various concentrations mixed with synthetic ester, included using surfactant oleic acid mixed with base liquid at 0.75wt% on the AC dielectric strength. Otherwise, like in the reference studies [11, 33], a surfactant with a span80 of around 0.7 g/1 g (nano) was applied to several nanoparticles of TiO_2, ZnO, and $BaTiO_2$ mixed with mineral oil to determine their electrical properties. Moreover, a surfactant, Sorbitan monooleate (Span™ 80), has a hydrophile-lipophile balance (HLB) of 4.3, which is in the range of 3–6 considered suitable for water in petroleum or mineral oil and mass volume between nanoparticles and surfactants. Therefore, in this research, the appropriate ratio for the addition of a Span™ 80 of 0.7 g/1 g (nano) was applied to Fe_3O_4 nanoparticles mixed with mineral oil to determine their electrical and physical properties.

3. Testing Preparation

3.1. Preparation of Nanofluids-Based Mineral Oil-Impregnated Pressboard. Pressboard pieces 80 × 80 mm in size were prepared, placed in the test chamber, and dried in a vacuum cabinet at 105°C under a pressure of −0.08 MPa for 24 h to extract moisture and were compliant with IEC 60641–2 [34]. Pressboard samples were ready for mineral oil impregnation, as shown in Figure 2.

There were five steps in preparing nanoparticle-based mineral oil for impregnation of pressboard samples that were obtained according to IEC 60641–2, as shown in Figure 3. The first step involved preparing the mixture of Fe_3O_4 nanoparticles at the ratios of 0.01 wt%, 0.03 wt%, and 0.05 wt% by mineral oil volume; surfactants were added at the ratio of 70% by nanoparticle volume [2, 33]. Then, nanoparticle-based mineral oil was stirred by using a magnetic stirrer at 60°C for 30 minutes. To enable an effective mixture of nanoparticles in mineral oil, the third step was to place them in an ultrasonic vortex mixer at 60°C for 2 h. Subsequently, nanoparticle-based mineral oil was reduced to low humidity by using a vacuum hot air dryer at 80°C for 24 h to extract the moisture content; the mineral oil was ready for impregnation of pressboard samples prepared in the previous step. Finally, pressboard samples were impregnated in the prepared mineral oil for 24 hours in a vacuum cabinet at 80°C with a pressure of 0.08 MPa to remove moisture content from both the mineral oil and the pressboard samples.

3.2. Parameters and Design of the Test Vessel for Measuring the Voltage Strengths of Insulating Pressboard. A test vessel was designed and constructed according to IEC 60641–2 [34], IEC 60243–1 [35], IEC 60243–3 [36], and IEC 60897 [37] standards to measure AC voltage strengths and lightning impulse voltage strengths. The brass electrode holders used in the test vessel were composed of 3 mm radius-curved cylindrical upper-lower electrodes: the first electrode was 25 ± 1 mm in diameter and 25 mm in height, and the second was 25 ± 1 mm in diameter and 25 mm in height. The test vessel for storing mineral oil and placing pressboard was constructed with transparent acrylic and was a cylinder 160 mm in diameter and 3 mm in thickness. Moreover, the

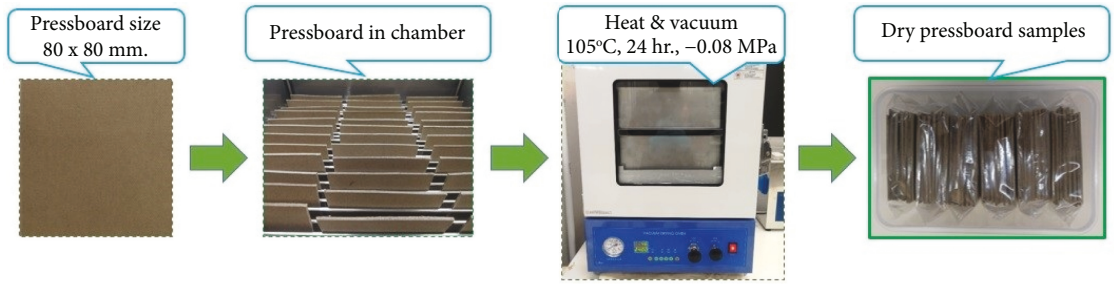


Figure 2: Preparation of pressboard samples.

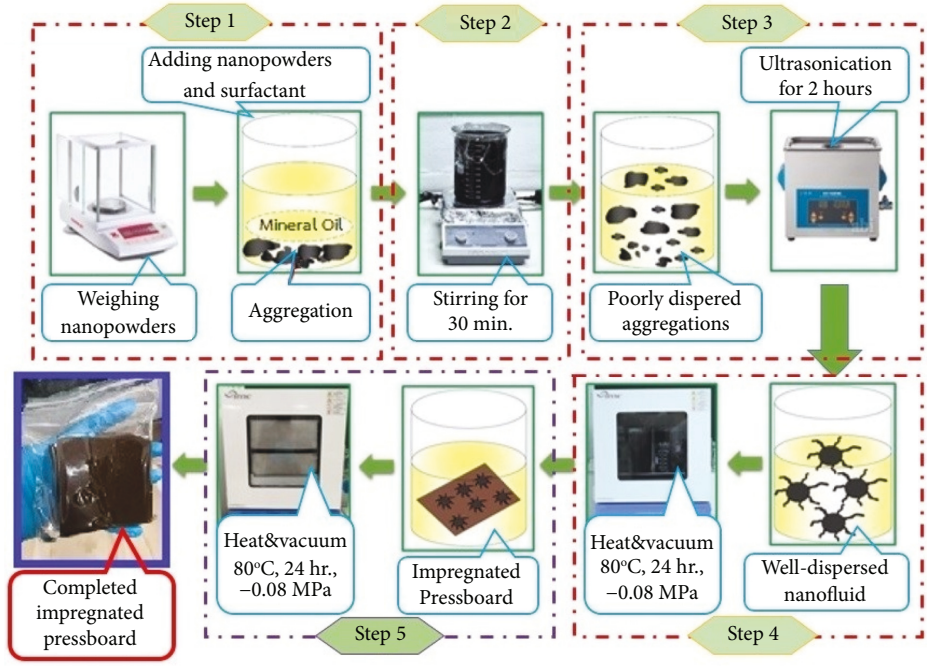
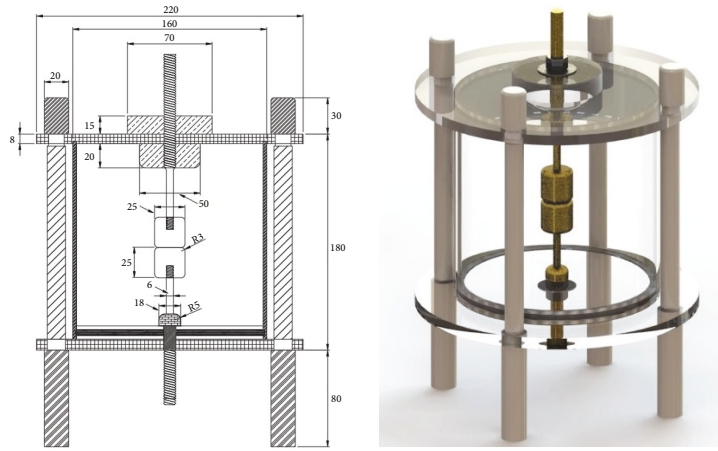


Figure 3: Preparation of nanoparticle-based mineral oil and impregnation of pressboard samples.

upper and lower bases of the acrylic cylinder were made of acrylic round discs with a hole drilled for fixing electrode holders; a groove was also made to place a rubber water stop in the joint between the lower base and the acrylic cylinder. Details of the test vessel are shown in Figure 4.

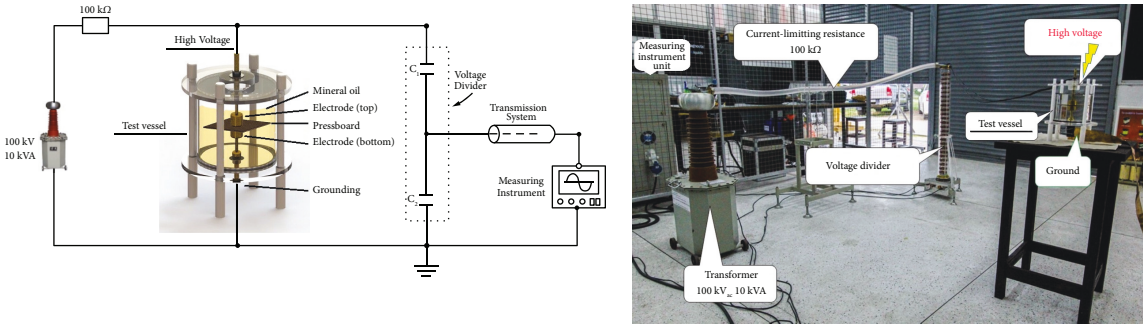
3.3. Investigation of the Electrical Properties of the AC Breakdown Voltage. Tests of AC breakdown strengths were performed with pressboard immersed in nanoparticle-based mineral oil and conventional mineral oil. Tests were conducted through a 100 kV_{AC}, 10 kVA test set. An equivalent circuit for testing and circuit preparation for measuring AC breakdown strengths of pressboard according to IEC 60641–2 [34] and IEC 60243–1 [35] is shown in Figure 5. Initially, liquid insulating samples were gradually filled into the test vessel at a volume of 2,100 mL. Samples of pressboard impregnated with nanoparticle-based mineral oil were then placed in the test vessel, left for five minutes, and checked for any air bubbles. If there are any remaining air bubbles, use a stirring rod to gently stir the samples until the air bubbles are exhausted. Subsequently, voltages were increased in steps of 5 kV/s until breakdown was manifested. Afterwards, the AC breakdown value displayed on a voltmeter was recorded. Once the tested insulating pressboard underwent breakdown, the new pressboard sample was further tested in place of the prior one. A five minute interval between each test was allowed, and the processes were iterated until six tests were successfully carried out following the standard. Upon completion, the average values were recorded.

3.4. Investigation of the Electrical Properties of the Lightning Impulse Breakdown Voltage. The lightning impulse breakdown strengths of pressboard impregnated with nanoparticle-based mineral oil were tested with the 400 kV, 40 kJ test set. An equivalent circuit for testing and circuit preparation for measuring lightning impulse breakdown strengths of pressboard based on IEC-60641-2 [34], IEC 60243–1 [35], and IEC 60243–3 [368 is shown in Figure 6. Initially, 2,100 mL of liquid insulating samples were gradually added into the test vessel. After five minutes, samples of pressboard impregnated with nanoparticle-based mineral oil



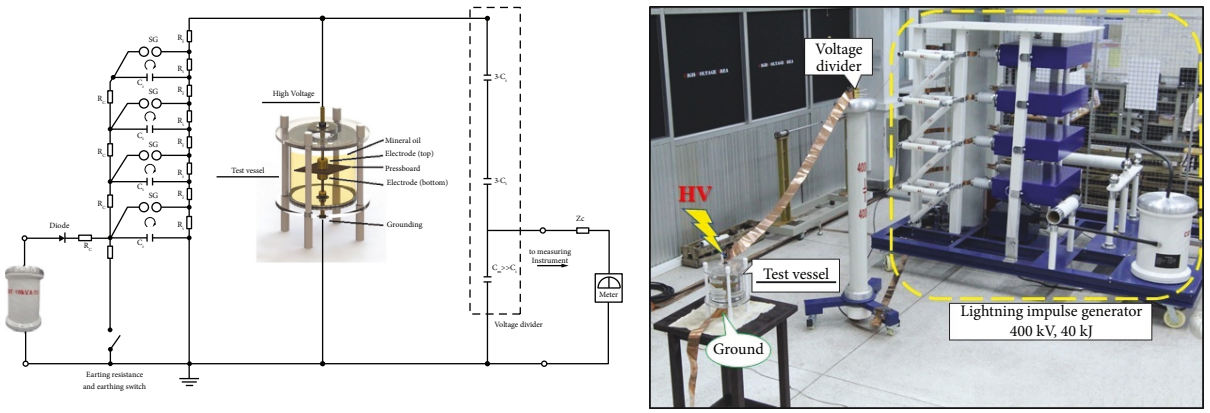
(a) (b)

FIGURE 4: The parameters and design of the test vessel for measuring the voltage strengths. (a) Details of test vessel design (mm). (b) 3D Test vessel design.



(a) (b)

FIGURE 5: Preparation for measuring AC breakdown strengths. (a) Equivalent circuit for AC breakdown testing. (b) Test circuit preparation.



(a) (b)

FIGURE 6: Test circuits for measuring lightning impulse breakdown voltage strengths. (a) Equivalent circuit for measuring lightning impulse breakdown strengths. (b) Test circuit preparation.

were put in the test vessel and monitored for any air bubbles until the air bubbles were exhausted.

At this point, impulse waveforms T_1 and T_2 were measured according to established criteria. That is, a wave-front period $T_1 = 1.2\,\mu s \pm 30\%$ must be in the range of 0.84–1.56 μs, and a wave-tail period $T_2 = 50\,\mu s \pm 20\%$ must be in the range of 40–60 μs. The pressboard can be tested with the impulse voltage at 50% of the breakdown point, or Ub

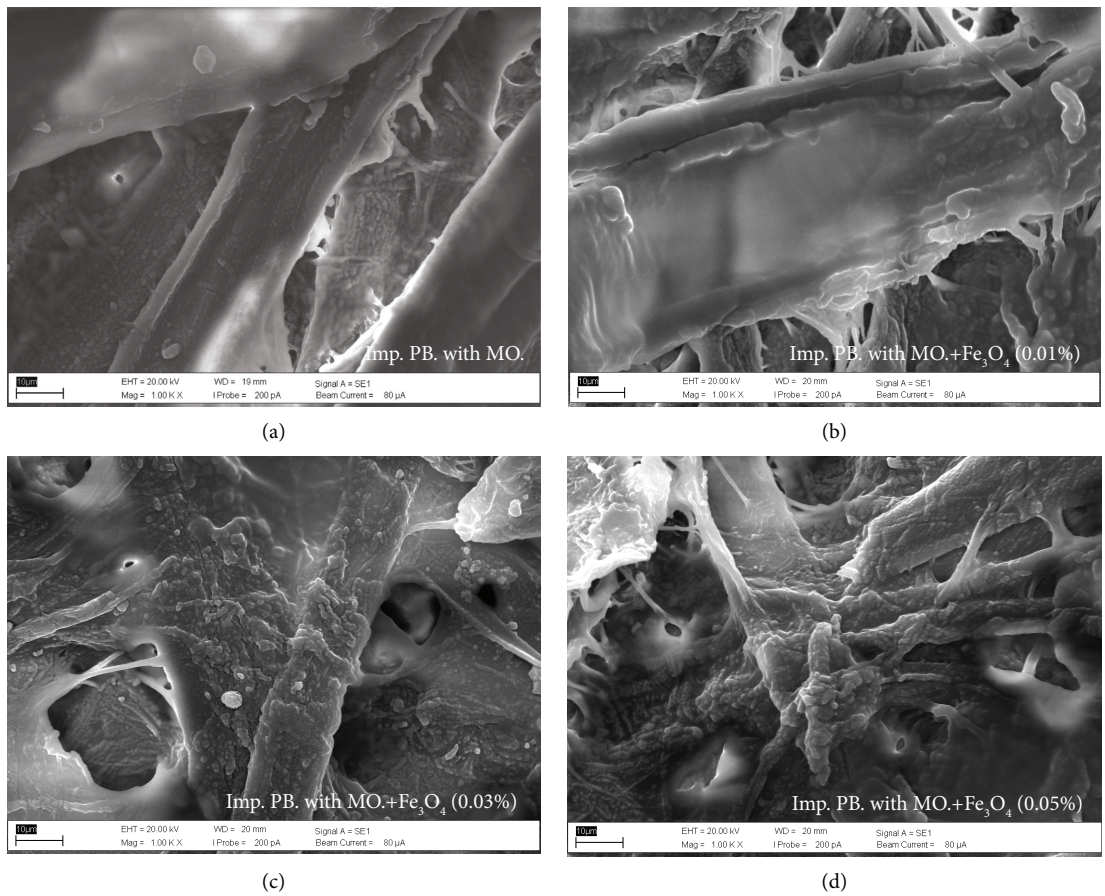


Figure 7: Scanning electron microscopy (SEM) images of the pressboard surface. (a) The surface features of impregnated pressboard with conventional mineral oil. (b) The surface features of impregnated pressboard with mineral oil-based Fe_3O_4 (0.01%). (c) The surface features of impregnated pressboard with mineral oil-based Fe_3O_4 (0.03%). (d) The surface features of impregnated pressboard with mineral oil-based Fe_3O_4 (0.05%).

(50%), according to testing standards. When the pressboard did not undergo breakdown, impulse voltages were increased in steps of 5 kV until breakdown was detected. Afterwards, the lightning impulse breakdown displayed on a voltmeter was recorded. Once the breakdown occurs, the new pressboard sample should be tested in place of the earlier one. Prior to starting a new test, a 5-minute interval between each test was allowed, and the processes were repeated until six tests were successfully carried out. Upon completion, the average values were recorded.

4. Results

4.1. Surface Analysis of Impregnated Pressboard by the SEM Method. The microstructures of modified pressboards are shown in scanning electron microscopy (SEM) (LEO, Model: 1450VP, Germany) micrographs in Figure 7.

Furthermore, Figure 7(a) shows the internal structure of a pressboard impregnated with traditional mineral oil impregnation. Similary, Figures 7(b)-7(d) show the internal structure differences of a pressboard impregnated with nanofluids of 0.01, 0.03, and 0.05, respectively. It was found that cellulose pressboard saturated with conventional mineral oil had fewer cellulose fibers bound together and compacted less than cellulose pressboard saturated with mineral oil-based nanofluids. While the amount of Fe_3O_4 nanoparticles adhering to the surface of cellulose pressboard tended to increase with the increase in the volume of nanoparticles. In particular, the increased number of nanoparticles causes the cellulose fibers in the pressboard to be bound together and compacted as the nanoparticles get into the tiny holes in the crossed fibers.

4.2. X-RD Analysis of the Impregnated Pressboard. The X-ray diffractometer (X-RD) (Bruker, Model: D8 Advance, Bruker BioSpin AG Company) was obtained in the 2θ range (0°–100°) and its pattern curves of impregnated pressboard with conventional mineral oil and mineral oil-based Fe_3O_4 nanomaterials are displayed in Figure 8. The electrical performance of crystalline polymer materials is determined by their crystal structure and crystallinity. Crystal structure identification and chemical phase analysis may be carried out by evaluating the length, breadth, height, and diffraction angle. As a result, X-RD analysis is extremely useful in

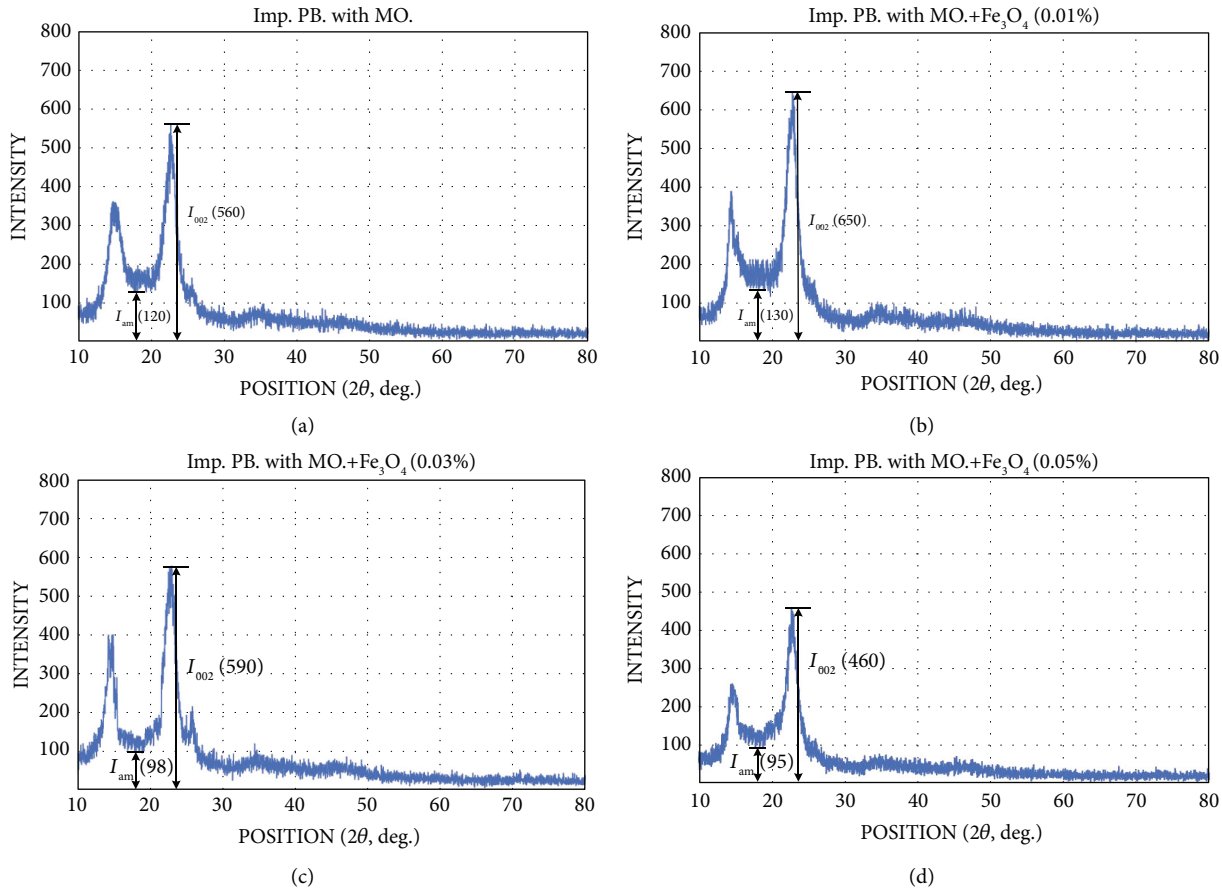


FIGURE 8: X-ray diffraction (X-RD) of the impregnated pressboard. (a) X-RD pattern of impregnated pressboard with conventional mineral oil. (b) X-RD pattern of impregnated pressboard with mineral oil-based Fe_3O_4 (0.01%). (c) X-RD pattern of impregnated pressboard with mineral oil-based Fe_3O_4 (0.03%). (d) X-RD pattern of impregnated pressboard with mineral oil-based Fe_3O_4 (0.05%).

determining the crystal structure of cellulose fibers in transformer pressboards [38].

Moreover, the following equation can be used to compute the relative crystallinity (CrI) of the transformer pressboard and can be expressed as follows [38–40].

$$\mathrm{CrI} = \left[\frac{I_{002} - I_{am}}{I_{002}}\right] \times 100\%, \quad (1)$$

where I_{002} and I_{am} represent the lattice diffraction's maximum intensity (at the 002 peak) and amorphous area diffraction intensity (at about $2\theta = 18.5^{\circ}$, the local minima of the intensity), respectively.

The 002-crystal face in cellulose is represented by the second peak, which emerges at about 22.5°. In the diffraction pattern of the impregnated pressboard with conventional mineral oil and mineral oil-based Fe_3O_4 nanoparticles, there is a strong peak and some dispersive diffraction peaks, indicating that the cellulose has a mixed structure of crystallization and amorphous phase [38–42]. The intensity variation of the impregnated pressboard with conventional mineral oil and the impregnated pressboard with mineral oil-based Fe_3O_4 nanofluids with variation in the crystallinity of the material is shown in Table 4. The crystal structure of cellulose fibers in transformer pressboards is improved to

TABLE 4: Results of the intensity and relative crystallinity of the impregnated pressboard.

Impregnated Pressboard Samples with	Intensity		Cr (%)
	I_{002}	I_{am}	
Mineral oil (MO)	560	120	78
MO + Fe_3O_4 (0.01%)	650	130	80
MO + Fe_3O_4 (0.03%)	590	98	83
MO + Fe_3O_4 (0.05%)	460	95	79

increase the crystallinity when the pressboards are impregnated with nanofluids. Especially in the amount of Fe_3O_4 nanoparticles at a rate of 0.03 vol% of the mineral oil, the crystallinity can be maximized.

Figure 8 shows that the characteristic peaks in the curve of the pressboard impregnated are identical to those of both impregnated pressboard with nanofluids-based mineral oil and conventional mineral oil. In addition, there is no other characteristic peak, which suggests that the addition of sorbitan monooleate in the process of preparing nanoparticle-based mineral oil for impregnation of pressboard samples can help control the diameter of Fe_3O_4 nanoparticles as follows in the process impregnates in section 3.1. Calcination at a temperature of 1000 °C for 2-4 hours is the

best method for producing ε-Fe2O3 nanoparticles in opal-like matrices. In mixes of iron oxide modifications, the percentage of ε-Fe2O3 fluctuates from 80-90%.. The insulating paper's typical X-RD pattern is shown in Figure 8. Between 14° and 24°, there are two distinct diffraction peaks. The 101 crystal faces in cellulose are represented by the first peak, which is in the range of 14°–15.5°.

4.3. AC Breakdown Voltage Strengths. Tests of the AC breakdown strengths of pressboard impregnated with nanofluids-based mineral oil and conventional mineral oil were performed in the test vessel according to the IEC 60641–2, and IEC 60243–1 standards. They were carried out six times to determine the average values. The results are displayed in Figure 9 and Table 5. The results of the AC breakdown strengths of pressboard impregnated in nanofluids-based mineral oil and conventional mineral oil are shown in Figure 9 and Table 5.

Under the same test condition, mineral oil-impregnated pressboard modified with Fe_3O_4 nanoparticles at 0.01 wt% achieved the higher breakdown strength. Compared to that of pressboard impregnated with conventional mineral oil, its breakdown strength rose by up to 5% under the same test condition. It was also found that the AC breakdown strength of mineral oil-immersed pressboard based on Fe_3O_4 nanoparticles at 0.03 wt% was increased by up to 12.83%, which was the highest of any conventional mineral oil, including Fe_3O_4 at any volume. Meanwhile, at a ratio of 0.05 wt%, its strength dropped to 3.79% when compared to that of impregnated pressboard with mineral oil-immersed pressboard based on Fe_3O_4 nanoparticles at 0.03 wt%, respectively. However, mineral oil-impregnated pressboard modified with Fe_3O_4 nanoparticles at 0.05 wt% still achieved a higher breakdown strength when compared to that of the pressboard impregnated with conventional mineral oil.

4.4. The Lightning Impulse Breakdown Voltage Strengths. The lightning impulse voltage breakdown strength test of pressboard immersed in Fe_3O_4 nanofluids-based mineral oil adhered to the IEC 60641–2 and IEC 60243–1 standards. This test was conducted to assess the impulse breakdown properties of pressboard. The average values of impulse breakdown were then used to determine the quality of pressboard. The test was performed six times to find the average values. In addition, the strength of the lightning impulses' breakdown voltage was evaluated to determine the insulating pressboards' relevant qualities. The mean values for the breakdown records were used to estimate the quality of the impregnated pressboards with conventional mineral oil, and hence the quality of the nanofluids obtained from the insulating pressboards. Variables like the volume content of Fe_3O_4 nanoparticles have been demonstrated to impact impulse breakdown strength in experiments. The process by which nanofluids impact the breakdown characteristics of insulating pressboards has yet to be fully understood. The increased insulating characteristics of the impregnated pressboard with mineral oil-based Fe_3O_4 are not explained by the standard idea of liquid dielectric dissolution. The

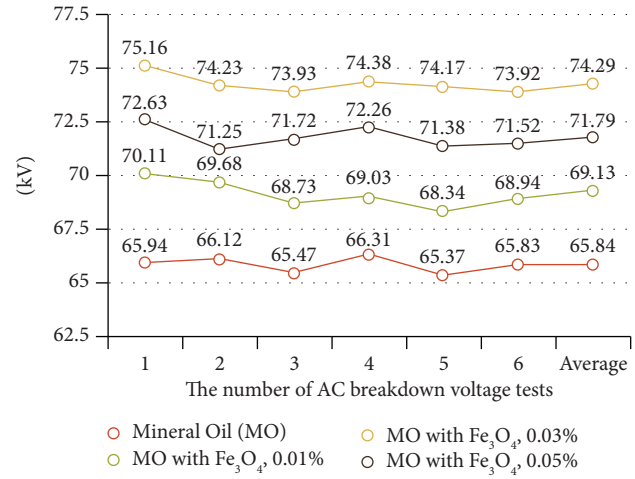


Figure 9: Comparison of the AC breakdown strengths of the impregnated pressboard.

Table 5: Results of the AC breakdown strengths of the impregnated pressboard.

Impregnated Pressboard Samples with	AC breakdown strengths (kV)		SD
	Average	kV/mm	
Mineral Oil (MO)	65.84	41.15	0.36
MO + Fe_3O_4 (0.01%)	69.13	43.20	0.64
MO + Fe_3O_4 (0.03%)	74.29	46.43	0.45
MO + Fe_3O_4 (0.05%)	71.79	44.86	0.54

*SD = Standard deviation of the data on AC tests.

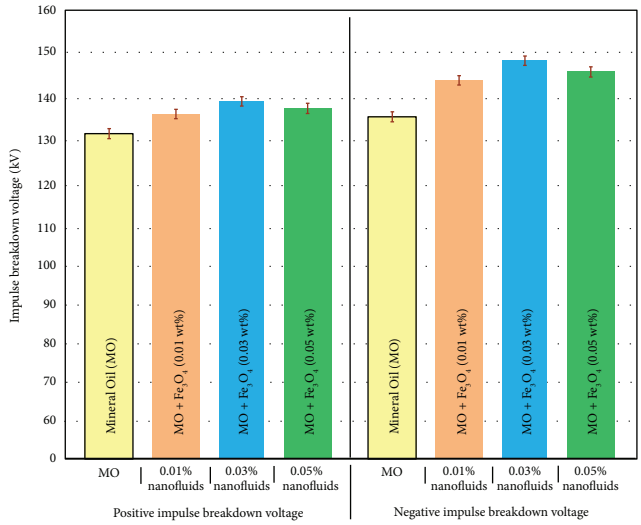


Figure 10: Average values of lightning impulse breakdown voltage strengths of pressboard impregnated with nanofluids-based mineral oil.

positive lightning impulse breakdown strengths of impregnated pressboard are shown in Figure 10 and Table 6. This shows that mineral oil-impregnated pressboard with Fe_3O_4 nanofluids at 0.01 wt% had a higher positive lightning impulse breakdown strength; specifically, its strength

Table 6: Results of the lightning impulse breakdown voltage of the impregnated pressboard.

Polarity	Lightning impulse breakdown voltage (kV)				% Increase		
		Impregnated Pressboard Samples with			Impregnated Pressboard Samples with		
	MO	MO + Fe_3O_4 at 0.01%	MO + Fe_3O_4 at 0.03%	MO + Fe_3O_4 at 0.05%	MO + Fe_3O_4 at 0.01%	MO + Fe_3O_4 at 0.03%	MO + Fe_3O_4 at 0.05%
Positive	132.7	136.5	139.3	137.8	2.86	4.97	3.84
Negative	135.9	144.4	147.3	145.1	6.25	8.39	6.77

increased by up to 2.86% when compared to conventional mineral oil. Moreover, the results also showed that mineral oil-immersed pressboard based on Fe_3O_4 nanofluids of 0.03 wt% had the highest lightning impulse breakdown strength. It increased by approximately 4.97% when compared to that of impregnated pressboard in nonmodified mineral oil. Similarly, at a ratio of Fe_3O_4 nanofluids of 0.05 wt%, its strength rose by up to 3.84% when compared to that of pressboard with conventional mineral oil. Meanwhile, its strength dropped to 1.55% when compared to that of impregnated pressboard with mineral oil-immersed pressboard based on Fe_3O_4 nanofluids at 0.03 wt%. However, mineral oil-impregnated pressboard enhanced with Fe_3O_4 nanofluids at 0.05 wt% exhibited a higher breakdown strength than standard mineral oil-impregnated pressboard.

Besides, Figure 10 and Table 6 depict the negative lightning impulse breakdown strengths of impregnated pressboard. Under the same test conditions, mineral oil-impregnated pressboard modified with Fe_3O_4 nanofluids at 0.01 wt% had a higher negative lightning impulse breakdown strength when compared to pressboard immersed in conventional mineral oil. The negative lightning impulse breakdown strength increased by up to 6.25%. In addition, for the pressboard impregnated with mineral oil based on Fe_3O_4 nanofluids of 0.03 wt%, the negative lightning impulse breakdown strength rose to the highest when compared to the impregnated pressboard with conventional mineral oil. The mineral oil-immersed pressboard modified using Fe_3O_4 nanofluids rose by approximately 8.39%. In the same way, the negative lightning impulse breakdown strength of the pressboard impregnated with mineral oil based on Fe_3O_4 nanofluids of 0.05 wt% went up by 6.77% when compared to conventional mineral oil. However, its strength declined by 1.62%, when compared to impregnated pressboard modified with Fe_3O_4 nanofluids at 0.03 wt%. When compared to pressboard impregnated with normal mineral oil, mineral oil-impregnated pressboard enhanced with Fe_3O_4 nanofluids at 0.05 wt % still had a greater breakdown strength.

5. Discussion

The addition of Fe_3O_4 magnetic nanoparticles to the mineral oil improves the mean AC breakdown voltage and the lightning impulse breakdown voltage of insulating pressboard, with Fe_3O_4 nanofluids at 0.03 percent having the highest maximization, and the nanoparticle loading at 0.05 percent decreases the AC breakdown voltage and the lightning impulse breakdown voltage. A similar trend has been identified in many other published research in the field [22, 43–46]. The field distribution is regulated by the relative permittivity of each dielectric under AC and the lightning impulse voltage due to the short period.

Mineral oil, Fe_3O_4 nanoparticles, and insulating pressboard are the three types of dielectrics used in the nanofluid impregnated pressboard. The conductivity of the dielectric under the impact of a continuous electric field determines the electric field distribution inside the dielectric according to the breakdown theory of composite dielectrics.

Moreover, the relative dielectric constant of Fe_3O_4 magnetic nanoparticles is higher than that of mineral oil in the nanofluids impregnated pressboard insulating system. An equation may be used to calculate the interface charge (δ) of the nanoparticle-mineral oil.

$$\varepsilon_{np}E'_{np} - \varepsilon_{mo}E'_{mo} = \delta, \tag{2}$$

and

$$\varepsilon_{np}E_{np}'' - \varepsilon_{mo}E_{mo}'' = 0, \tag{3}$$

where ε_{mo} represents the relative dielectric constant of mineral oil. $E'_{np}E_{np}''$, E'_{mo}, and E_{mo}'' are the vertical and parallel electrical fields of the nanoparticles and mineral oil, respectively. Moreover, because the pressboard's relative dielectric constant is higher than that of mineral oil, a bigger electrical field is generated in the direction parallel to the pressboard. In the discharge process, the electric field force of the interface charge will lead the free charge in the oil to travel in the direction of the pressboard. In other words, the streamer grows in the same direction as the pressboard. If the relative dielectric constant of the oil is larger than that of the pressboard, the charge at the pressboard-mineral oil interface repels the charge in the mineral oil, causing the streamer to develop into the mineral oil. Because mineral oil and pressboard have different relative dielectric constants, the interfacial charge (δ), as shown by (4) and (5) [22]:

$$\varepsilon_{pb}E'_{pb} - \varepsilon_{mo}E'_{mo} = \delta, \tag{4}$$

and

$$\varepsilon_{pb}E_{pb}'' - \varepsilon_{mo}E_{mo}'' = 0, \tag{5}$$

where ε_{pb} represents the relative dielectric constant of the pressboard. E_{pb}' and E_{pb}'' are the vertical and parallel electrical fields of the pressboard, respectively.

The electric field force created by the interface charge will attract the charge in the mineral oil because the relative dielectric constant of nanoparticles is larger than that of

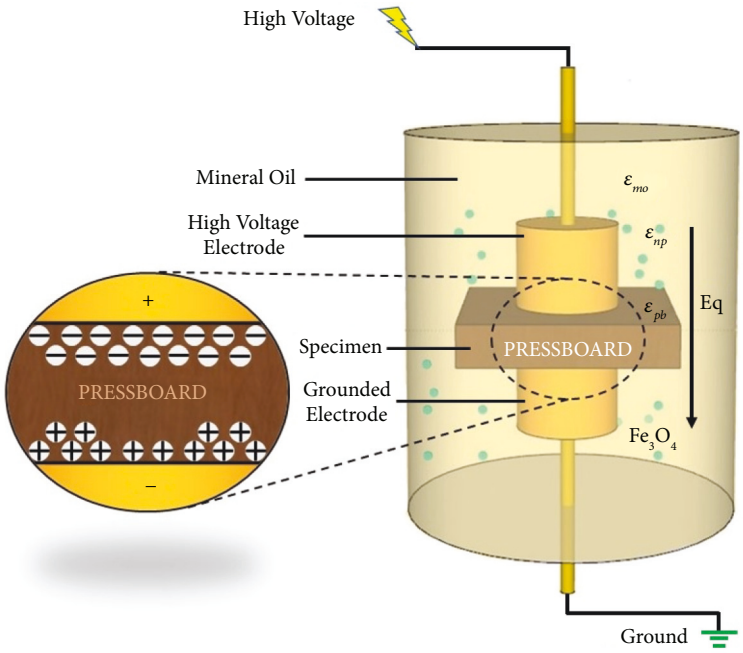


Figure 11: Schematic diagram of electric field distribution and space charge grouping of impregnated pressboard with mineral oil-based Fe_3O_4 nanoparticles.

mineral oil. As a result, as illustrated in Figure 11, the propagation of streamers in nanofluids impregnated pressboard will result in higher branch growth in the oil than traditional mineral oil-impregnated pressboard [22, 46, 47].

Furthermore, because the nanoparticles' relative dielectric constant is higher than that of mineral oil, the electric field force created by interface charge will attract the charge in the mineral oil. In mineral oil, the total force F of the point charge q is:

$$F = F_1 - F_2, \tag{6}$$

where F_1 is the force exerted by the mineral oil interface charge on the pressboard, which may be represented as:

$$F_1 = \frac{q \cdot q_1'}{4\pi\varepsilon_0 (2d_1)^2} \vec{e}, \tag{7}$$

where q is a point charge in the oil, with d_1 and d_2 being the distance to the pressboard and a nanoparticle, respectively. The vacuum permittivity is ε_0, and $\vec{e}$ is the unit direction vector of the vertical pressboard. d_1 is the internal distance of the pressboard on the equivalent mirror charge (q_1'), q_1' can also be expressed as .

$$q_1' = q\frac{\varepsilon_{mo} - \varepsilon_{pb}}{\varepsilon_{mo} + \varepsilon_{pb}}, \tag{8}$$

where F_2 is the force by the nanoparticles with mineral oil interface charge to point charge being expressed as .

$$F_2 = \frac{q \cdot q_2'}{4\pi\varepsilon_0 (2d_2)^2} \vec{e}, \tag{9}$$

where d_2 is the internal distance of the pressboard on the equivalent mirror charge q_2', q_2' can be expressed as:

$$q_2' = q\frac{\varepsilon_{mo} - \varepsilon_{np}}{\varepsilon_{mo} + \varepsilon_{np}}. \tag{10}$$

Integrating (7)–(10), the total force F of point charge q in the mineral oil, with distance to the pressboard and a nanoparticle taken as d_1 and d_2, respectively, can be expressed as:

$$F = \frac{q^2\left(\varepsilon_{mo} - \varepsilon_{pb}\right)}{16\pi\varepsilon_0 d_1^2\left(\varepsilon_{mo} + \varepsilon_{pb}\right)^2} \vec{e} - \frac{q^2\left(\varepsilon_{mo} - \varepsilon_{np}\right)}{16\pi\varepsilon_0 d_2^2\left(\varepsilon_{mo} + \varepsilon_{np}\right)^2} \vec{e}. \tag{11}$$

In Equation (11), this will demonstrate the effect of nanoparticles on streamer propagation. The total force F of the point charge q in the mineral oil is based on the assumption that the pressboard impregnated with nanofluid contains n nanoparticles. From Equation (11), as can be observed, unmodified mineral oil-impregnated pressboard just has a pressboard interface charge that has an impact on the charge. Because of $\varepsilon_{mo} < \varepsilon_{pb}$, the charge in the mineral oil is drawn to the interface charge and reversed to the interior of the pressboard. Moreover, the charge in the mineral oil moves around the nanoparticles because of the interface charge by nanoparticles with mineral oil, lowering the attraction by the pressboard, resulting in a high number of lateral branches developing in the mineral oil during the discharge process. In addition, the pressboard's ability to withstand a breakdown strength drops because an excess of nanoparticles made it more difficult to disperse particles while impregnating pressboard samples under the same preparation conditions in other volumes, thus causing

dispersion of the nanoparticles to be reduced and the nanoparticles to accumulate in larger clumps on the pressboard surface, as seen in Figure 7. This is consistent with the crystallinity summary results in Figure 8 and Table 4. The intensity and relative crystallinity of the impregnated pressboard decrease as the nanoparticle volume ratio increases. As a result, the properties of nanomaterials and pressboard slightly change.

6. Conclusions

The study sheds some light on the effect of Fe_3O_4 magnetic nanoparticle concentrations on the electrical properties of mineral oil-based nanofluids impregnated on pressboard. The results showed that the Fe_3O_4 magnetic nanoparticles at 0.01 wt%, 0.03 wt%, and 0.05 wt% being added to the mineral oil for impregnated pressboard can give an increase in the electrical properties of pressboard. Moreover, the optimum nanofluid combination in terms of impregnated pressboard that increased the AC breakdown voltage strength was created by adding Fe_3O_4 to mineral oil at a rate of 0.03 vol%. In the meantime, the positive and negative lightning impulse breakdown strengths of impregnated pressboard modified using all quantities of nanoparticles-based mineral oil are more resistant to breakdown voltage than conventional mineral oil-impregnated pressboard insulation. In particular, the use of nanoparticles at 0.03 wt% also increased the most. It can also be observed that the increased number of nanoparticles causes the cellulose fibers in the pressboard to be bound together and compacted as the nanoparticles get into the tiny holes in the crossed fibers, i.e., the crystal structure of cellulose fibers in transformer pressboards is improved to increase the crystallinity. This can be maximized when the pressboards are impregnated with Fe_3O_4 nanofluids at a rate of 0.03 vol% of the mineral oil. These findings point to interesting new approaches for using Fe_3O_4 magnetic nanoparticles to improve the electrical characteristics of insulating pressboard.

Data Availability

The reference articles' data used to support the findings of this study are included within this article.

Conflicts of Interest

The authors declare no conflicts of interest.

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