

AC Breakdown Performance of Organic Transformer Oil Using Different Nano Oxide Fillers of ZnO, NiO and α -Fe₂O₃

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DOI: <https://doi.org/10.30880/ijie.2024.16.07.028>

Article Info

Received: 27 June 2024

Accepted: 17 November 2024

Available online: 31 December 2024

Keywords

AC breakdown performance, organic transformer oil, nano oxide

Abstract

The AC breakdown performance of traditional insulating oils in transformers is often inadequate, leading to operational inefficiencies and environmental concerns. There is a growing need for alternatives that enhance transformer performance while being environmentally sustainable. This paper investigates the AC breakdown performance of organic transformer oil, specifically using vegetable oil, mixed with Iron Oxide Hematite (α -Fe₂O₃), Zinc Oxide (ZnO), and Nickel Oxide (NiO) nanoparticles (NPs). These NPs are incorporated into the organic transformer oil to form Nano Fluids (NFs). The study examines the effect of NPs with different concentrations on the AC breakdown voltage (AC-BDV) of organic transformer oil. The One Minute Power Frequency Test is employed to test the AC-BDV, while X-ray diffraction (XRD) characterizes the structural properties of the NPs. The results indicate that NFs containing 6g of (α -Fe₂O₃) NPs and 6g of (ZnO) NPs exhibit the most significant improvement in AC-BDV, showing enhancements of approximately 49.86% and 40.17%, respectively. Furthermore, NFs based on (α -Fe₂O₃) with a concentration of 0.01g/ml outperform other NPs, demonstrating an average breakdown voltage of 13.525 kV. Consequently, the experimental analysis concludes that (α -Fe₂O₃) based NFs offer effective electrical insulation, serving as a potential substitute for mineral oil in transformers. This innovation not only improves transformer performance but also aligns with environmental concerns, particularly the shift from mineral oil to biodegradable options like organic transformer oil. Different types of nanoparticles and their concentrations directly impact the AC breakdown voltage, underscoring the potential of nanoparticle-infused organic transformer oil in transforming traditional insulating systems.

1. Introduction

High voltages find extensive use in power generation, transmission, and distribution across various sectors, including power systems, industries, and research facilities. Ensuring the dependability of high-voltage systems relies on the optimal functioning of all system components, such as high-voltage transformers. These transformers hold significant importance and are valuable assets in high-voltage applications. Their primary role involves voltage conversion, both stepping up and down the generated voltage for customer supply. Failure of a transformer could have catastrophic effects. This line of inquiry was explored by [1] as well. In Malaysia, mineral oil (MO) has traditionally been used as the insulating fluid in high voltage (HV) oil-filled equipment, such as power transformers, bushings, tap changers, cables, power capacitors, and circuit breakers. The power distribution transformers owned by Tenaga Nasional Berhad (TNB), Malaysia's main power utility, are also insulated with petroleum-based oil. Similar research was performed by [2]. This preference for mineral oil is due to its superior dielectric strength and heat transfer efficiency, both of which are critical for transformer insulation systems. However, to maintain the transformer's safe and efficient operation, further enhancement of mineral oil's insulating properties is essential.

A promising method to improve these properties is by adding nanoparticles to mineral oil (MO). Recent investigations by [3-8] have underscored the endeavors of many researchers to boost the dielectric properties of transformer oil through nanoparticle incorporation. According to [9], there is significant interest among researchers in exploring nanoparticles that offer enhanced electrical conductivity and insulation properties to mitigate agglomeration issues. The inclusion of nanoparticles is anticipated to strengthen mineral oil. Research by Khaled and [10] supports this, demonstrating that the addition of specific nanoparticles can substantially enhance the AC dielectric strength of MO-based nanofluids. Extensively studied nanoparticles include iron oxide (Fe_3O_4), aluminium oxide (Al_2O_3), silicon dioxide (SiO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), copper oxide (CuO), fullerene (C_{60}), and aluminium nitride (AlN). This topic has also been investigated by [11].

Recent studies have explored various nanoparticles to enhance the dielectric properties of transformer oils. Iron oxide (Fe_3O_4), for example, is favored for its distinct electrical and magnetic characteristics, which significantly improve AC-BDV. Fe_3O_4 nanoparticles have shown promising results, with enhancements in AC-BDV by more than two times when added to mineral oil [12,13]. However, challenges such as optimal concentration and agglomeration issues remain.

Aluminium oxide (Al_2O_3) nanoparticles are known for their excellent thermal conductivity and stability, which contribute to better heat dissipation and improved dielectric strength. Silicon dioxide (SiO_2) offers superior insulation properties and enhances the thermal stability of transformer oils. Titanium dioxide (TiO_2) is appreciated for its high dielectric constant, which aids in increasing the overall dielectric strength of the oil. Zinc oxide (ZnO) and copper oxide (CuO) are also studied for their electrical properties, though they can be more expensive and may present challenges in achieving uniform dispersion.

Fullerene (C_{60}) and aluminium nitride (AlN) nanoparticles are notable for their unique structures and properties. Fullerenes, with their spherical shape, can enhance the breakdown voltage by providing a stable and uniform dielectric environment. Aluminium nitride, with its high thermal conductivity and electrical insulation properties, also shows potential for improving transformer oil performance. However, the cost and potential long-term stability issues of these nanoparticles need to be considered.

Due to its non-biodegradable nature, the widespread use of mineral oil as an insulator raises environmental concerns. [14] undertook a study with a similar focus. The current body of research predominantly focuses on the advantages of nanoparticle dispersion in mineral oil. However, there is a significant gap in research regarding the integration of nanoparticles with vegetable cooking oil, signaling a critical shift in exploration.

In addition to vegetable cooking oils, research has explored the use of synthetic ester oils as an environmentally friendly alternative to mineral oils in transformer applications. Synthetic ester oils offer several advantages, including higher moisture tolerance, biodegradability, and flame resistance characteristics, making them suitable for replacing mineral oils [15]. Studies have shown that both natural ester oils (e.g., sunflower oil, rapeseed oil, coconut oil, palm oil) and synthetic esters enhance the transformer's lifetime and loading ability while providing better biodegradability and higher flash and fire points compared to conventional mineral oils [16,17]. These properties make ester oils, both natural and synthetic, a preferred choice for improving the environmental and operational performance of transformers.

Therefore, while significant progress has been made in enhancing the dielectric properties of mineral oils with nanoparticles, further research into the potential of nanoparticle-enhanced natural and synthetic ester oils is necessary. This could lead to more sustainable and environmentally friendly insulating fluids for transformer applications. This research aims to transform transformer insulation by substituting conventional mineral oil with environmentally friendly alternatives, specifically focusing on vegetable cooking oil. The exploration of vegetable cooking oil as a potential insulating material aligns with the global trend toward biodegradable and renewable resources, addressing the need for environmentally friendly solutions and environmental consciousness. This

shift underscores a broader commitment to ecologically responsible and sustainable practices in the field of electrical engineering, contributing to the alleviation of environmental concerns associated with mineral oil.

Breakdown voltage is a measure of the electrical stress that an insulating oil can withstand without breakdown, indicating its resistance to electric shock in electrical devices [18,19]. Among the various parameters, the AC breakdown voltage is particularly critical. AC breakdown voltage is a key factor in assessing the performance and reliability of transformer oil under alternating current conditions, which is the most common operating condition for transformers. A high AC breakdown voltage signifies the oil's strong insulating properties and its ability to prevent electrical failures. The dielectric breakdown test, which measures the AC breakdown voltage, is therefore an essential part of the acceptance criteria for insulating oil in transformers [20]. If the AC breakdown voltage of the oil falls below the specified limit, it can lead to several operational failures, compromising the safety and efficiency of the transformer [21].

According to studies by [12,13], adding iron oxide (Fe_3O_4) to mineral oil can significantly enhance the AC breakdown voltage (AC-BDV). The actual ACBDV of mineral oil before the addition of Fe_3O_4 was 38.50 kV. After incorporating Fe_3O_4 nanoparticles at concentrations of 0.3 g/L and 0.4 g/L, the ACBDV increased to 67.40 kV and 82.30 kV, respectively. This corresponds to improvements of 75.3% and 108.8%, demonstrating that Fe_3O_4 can more than double the ACBDV of mineral oil, thereby substantially enhancing its insulating properties. Iron oxide has garnered significant interest due to its distinct electrical and magnetic characteristics. Although promising outcomes have been observed, there is still a substantial lack of understanding regarding the optimal concentration and particular forms of nanoparticles needed to attain the highest increase in AC-BDV in vegetable cooking oil. This transition stems from a reevaluation of transformer insulating materials prompted by a growing environmental awareness. This knowledge gap hinders the full harnessing nanoparticles for superior electrical insulation and poses a significant challenge to the practical implementation of this approach in electrical systems.

The aim of this study is to assess the performance of AC-BDV in vegetable cooking oil mixed with various types and quantities of nanoparticles. Consequently, the primary contribution of this paper is to address a knowledge gap in the research by conducting an extensive literature review on vegetable cooking oil and its NFs, discussing their potential as environmentally friendly transformer oils. The main objectives are to evaluate AC-BDV at various nanoparticle concentrations and types and to scrutinize the effectiveness of vegetable cooking oil as a liquid insulator. The secondary goal is to examine the behavior and suitability of vegetable cooking oil and its NFs as transformer oil. This study aspires to provide an accurate understanding of the literature, currently dominated by various forms of vegetable oil, and to highlight its shortcomings.

2. Methodology

This research adopted a detailed methodology to explore the impact of different nanoparticles (NPs) on the AC breakdown strength of vegetable cooking oil. Structural characteristics of the NPs were examined using X-ray Diffraction (XRD) analysis. The main objective was to identify optimal NP concentrations that improve the oil's AC breakdown performance. For high-voltage application studies, the One Minute Power Frequency test was employed, a technique also utilized by [22]. This test involved a high-voltage signal applied to the transformer's insulation to assess the breakdown voltage of the insulating oil.

The study's workflow, depicted in Figure 1, involved scanning the NPs with an X-ray Diffraction machine to analyze their properties. A geometrical model was constructed considering particle shape, wavelength, and crystallinity, drawing from previous research by [23]. Each NP type was assigned default parameters. The scanning procedure was conducted with a two-theta speed range from 20 to 90 degrees, at a rate of 10 minutes per degree, similar to the method used by [24].

The experimental stage was carried out, and the findings were conducted by comparing them with results from existing research. The X-ray diffraction experiment was repeated for each type of NP. Figure 1 outlines the parameters utilized in the experimental setup, providing a comprehensive overview of the methodology employed in this study.

2.1 Materials

This study examined the synthesis process of three distinct nanoparticles, Hematite, Zinc Oxide, and Nickel Oxide. The solution immersion method was chosen for synthesizing α - Fe_2O_3 , ZnO, and NiO nanopowders. The starting materials for synthesizing α - Fe_2O_3 , ZnO, and NiO nanopowders were Iron Chloride Hexahydrate ($\text{Cl}_3\text{Fe} \cdot 6\text{H}_2\text{O}$), Zinc Nitrate Hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), and Nickel (II) Nitrate Hexahydrate ($\text{N}_2\text{NiO}_6 \cdot 6\text{H}_2\text{O}$) respectively. Additionally, Urea ($\text{CH}_4\text{N}_2\text{O}$) functioned as the stabilizer for α - Fe_2O_3 , while Hexamethylenetetramine (HMT, $\text{C}_6\text{H}_{12}\text{N}_4$) was utilized as the stabilizer for ZnO and NiO. All nanoparticle solutions were meticulously prepared using deionized (DI) water obtained from the Millipore water purification system, serving as the solvent. This methodology was likewise employed by [23].

2.2 Experimental Work

To produce the nanopowders, a blend of Iron Chloride Hexahydrate ($\text{Cl}_3\text{Fe}\cdot 6\text{H}_2\text{O}$), Zinc Nitrate Hexahydrate ($\text{Zn}(\text{NO}_3)_2\cdot 6\text{H}_2\text{O}$), Nickel (II) Nitrate Hexahydrate ($\text{Ni}(\text{NO}_3)_2\cdot 6\text{H}_2\text{O}$), Urea ($\text{CH}_4\text{N}_2\text{O}$), Hexamethylenetetramine (HMT, $\text{C}_6\text{H}_{12}\text{N}_4$), and deionized water was used. Each chemical had a concentration of 0.4M in the mixed solution. The mixture was subjected to ultrasonication at 0°C for about 30 minutes using an ultrasonic water bath. Details of the ultrasonication setup are shown in Table 1. After this step, the solution was transferred into Schott bottles and heated in a 95°C water bath for four hours. The resulting $\alpha\text{-Fe}_2\text{O}_3$, ZnO, and NiO nanopowders were filtered and dried. Finally, the nanopowders were annealed at 500°C for one hour in a furnace. The procedure and schematic of the synthesis process of $\alpha\text{-Fe}_2\text{O}_3$, ZnO, and NiO using the immersion method are illustrated in Figure 2.

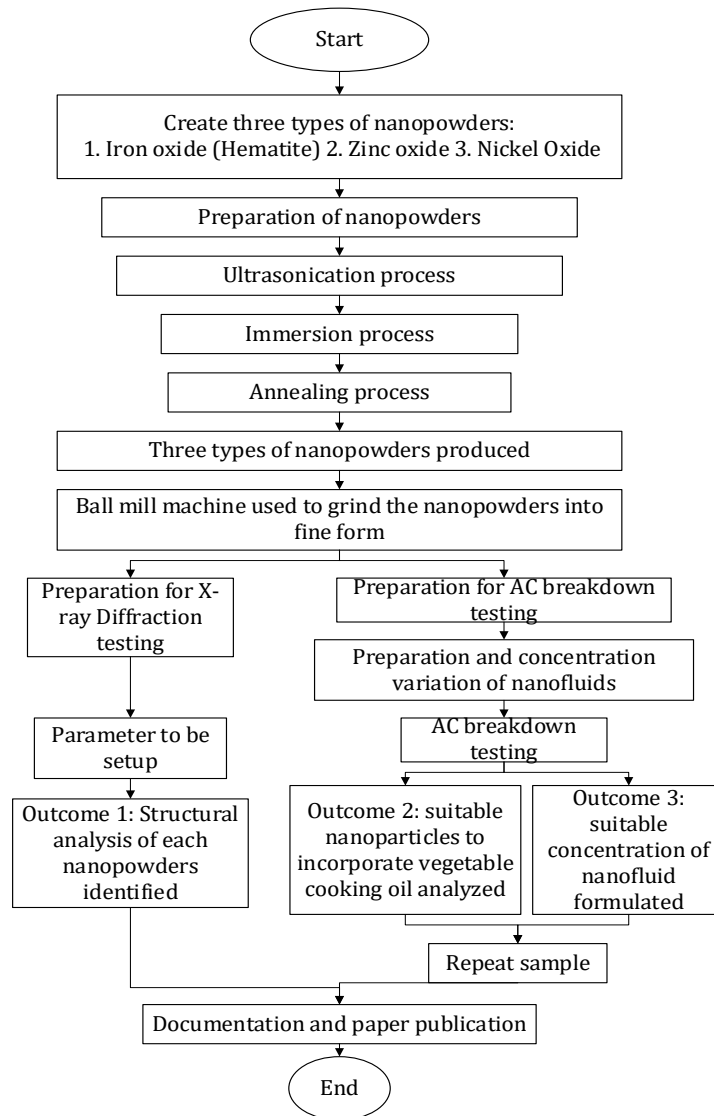


Fig. 1 Flowchart depicting the research methodology

Table 1 Ultrasonication parameters

Parameters	Value
Sonic Volume	Max value 3
Set Time (min)	60
Set Temp ($^\circ\text{C}$)	00
Sonic Temp ($^\circ\text{C}$)	21

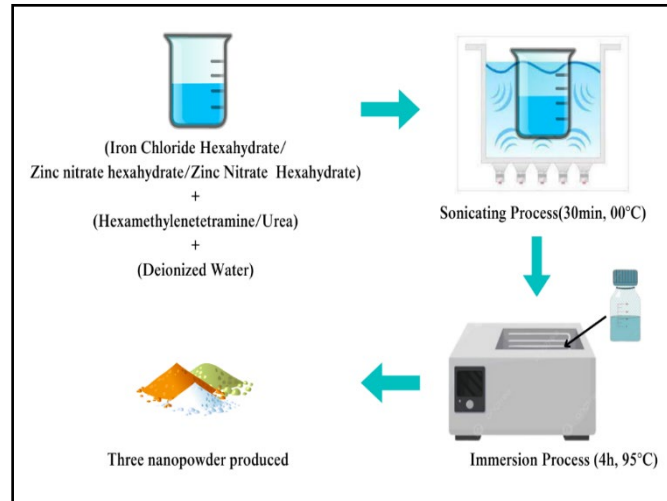


Fig. 2 The process of nanopowder production

2.3 Characterization

The structural characteristics of the α -Fe₂O₃, ZnO, and NiO nanopowders were evaluated using X-ray diffraction (XRD) analysis with the Rigaku Ultima IV system, utilizing Cu K-alpha radiation at a wavelength of 1.5418 Å. The synthesized nanoparticles can be analyzed using X-ray diffraction (XRD), which operates on Bragg's law ($n\lambda = 2d\sin\theta$), where 'n' represents an integer, 'λ' is the X-ray wavelength, 'd' is the atomic plane spacing, and 'θ' is the diffraction angle [25,26]. Identifying the types and compositions of the nanoparticles involves comparing observed diffraction peaks with reference standards, such as those provided by the International Centre for Diffraction Data (ICDD). Additionally, XRD helps assess the crystallinity of particles by examining the sharpness of the peaks in the diffractogram. The XRD patterns were recorded over a 2-theta range from 20° to 70°.

2.4 AC Breakdown Testing

The annealed nanopowders were combined with 600 ml of vegetable cooking oil to create NFs. These NFs were then subjected to a 1-hour, 0 °C ultrasonic bath. A test cell with minimum volume of 600 ml was utilized to ensure optimal immersion of the spherical mushroom-shaped electrode as shown in Figure 3.

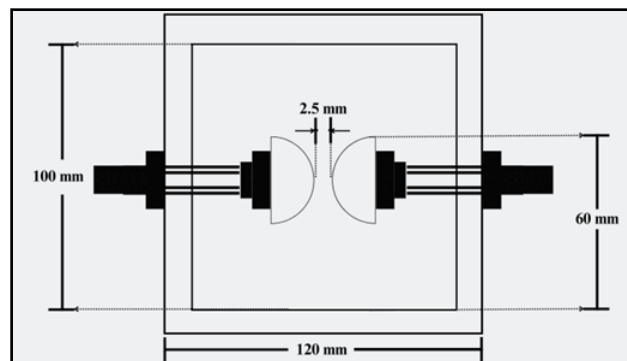


Fig. 3 Schematic diagram of breakdown voltage test cell

Prior to use, the test cell was cleaned using alcohol or ethanol to ensure the removal of any residual oils. This cleaning method aligns with the findings of [27]. According to recent findings by [28], the electrodes were spaced 2.5 mm apart. Afterward, the nanofluid (NF) sample was gently poured into the prepared test cell, as shown in Figure 4. The experimental setup for High Voltage Alternating Current (HVAC) testing at a frequency of 50 Hz is depicted in Figure 5. Detailed parameters for this procedure can be found in Table 3.

Table 2 presents a comprehensive overview of the seven distinct NFs subjected to rigorous testing in this study. These NFs vary in terms of the types and concentrations of nanoparticles meticulously incorporated into vegetable cooking oil. The diversity among these samples facilitates a thorough examination of the effects of different nanoparticle formulations on the AC-BDV performance. Each NF, identified by a unique combination of

nanoparticle type and concentration, contributes valuable insights into the potential enhancements in electrical insulation properties achievable with the utilization of various nanoparticles in vegetable cooking oil.

Table 2 Nanofluids sample

Sample	Weight of nanoparticles (g)	Types of nanoparticles	Volume of vegetable cooking oil (ml)	Concentration (g/ml)
S0	0	-	600	0
S1	3	Hematite	600	0.005
S2	3	Zinc Oxide	600	0.005
S3	3	Nickel Oxide	600	0.005
S4	6	Hematite	600	0.01
S5	6	Zinc Oxide	600	0.01
S6	6	Nickel Oxide	600	0.01

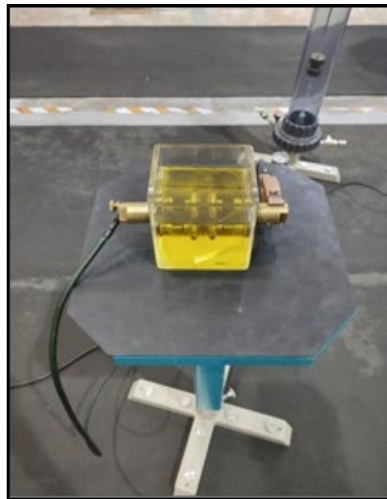


Fig. 4 Test cell on the table



Fig. 5 Experimental setup for HVAC

According to Table 3, the duration of this step is set at 1 minute. This aligns with the ISO standard, which specifies that a minimum of 1 minute is required for the voltage to be absorbed by the samples, inducing molecular

changes. [22] performed related research. In summary, the One Minute Power Frequency Test method emerges as the optimal approach to obtain accurate and precise results for AC breakdown testing of dielectric insulators.

Table 3 Testing parameters

Parameter	Value		
Limited voltage (kV)	40	Tolerance of step voltage (%)	2
Final voltage (kV)	30	No. of cycles	5
Start voltage (kV)	5	Duration of step	1 minute
Step voltage (kV)	1	Break duration	00:00:05
Rate of voltage rise (kV/s)	3		

Each nanofluid sample is documented over four cycles. Following the completion of two cycles, it becomes necessary to discharge the transformer. This supplementary step is recommended to allow the operator to assess the condition of the oils in the test cell. If a significant amount of carbon is generated due to breakdown, stirring is required for the nanofluid samples in the test cell. This is essential because the accumulated carbon tends to gather around the electrodes. [29] carried out a similar study. The average breakdown voltage (V_b) is determined using the following Equation (1).

$$V_b = \frac{V_{b1} + V_{b2} + V_{b3} + V_{b4}}{4} \quad (1)$$

The average breakdown voltage calculated was shown in Figure 7.

3. Results

3.1 Structural Analysis

The XRD analysis displayed in Figure 6 details the crystalline orientation of ZnO, α -Fe₂O₃, and NiO nanopowders. The ZnO sample's diffraction peaks matched those in PDF card no. 01-070-8072, confirming a polycrystalline, hexagonal wurtzite structure. The analysis revealed significant diffraction peaks for ZnO at the (100), (002), and (101) planes, along with additional peaks at (102), (110), (103), (200), (112), and (201), forming a complete pattern. The absence of impurity peaks in Figure 8 indicates the high purity of the ZnO nanopowder produced via the solution immersion method. The prominent diffraction peaks also highlight the excellent crystallinity of the ZnO nanopowder.

To evaluate the crystallinity properties of hematite (α -Fe₂O₃), X-ray diffraction (XRD) analysis was employed. As depicted in Figure 6, the XRD patterns of the nanopowders align with the key diffraction peaks of (α -Fe₂O₃), specifically (104), (110), and (024), indicative of a polycrystalline structure with rhombohedral lattice system under trigonal crystal system (PDF card no. 00-033-0664). Notably, no indications of other metal oxide phases, such as maghemite (γ -Fe₂O₃) or magnetite (Fe₂O₃), are evident in the XRD pattern.

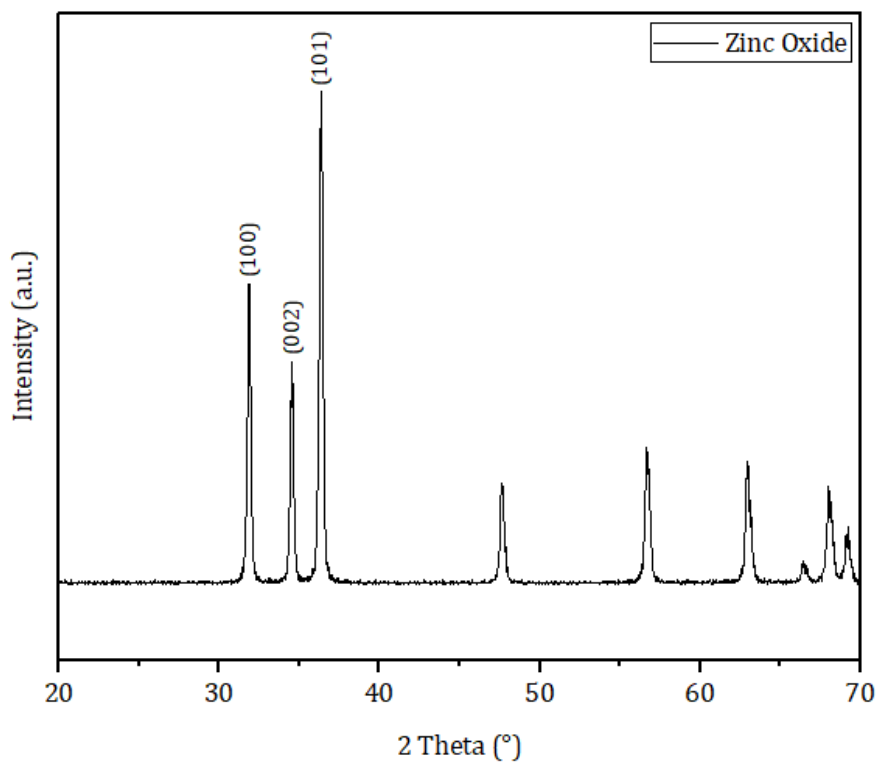
The X-ray diffraction pattern of the synthesized NiO, illustrated in Figure 6, adheres to the cubic phase based on the standard PDF card no. 01-073-1519. The most intense peak was identified on the (111) crystal plane, accompanied by additional peaks at (200), (220), (311), (222), (400), (331), (420), (422), and (511). The absence of crystalline contamination in the diffractogram affirms the impurity-free nature of the synthesized NiO material. This attests to the successful synthesis of NiO with a high degree of crystallinity and structural integrity.

Debye-Scherrer's formula was applied to estimate the crystallite size, D of each sample from the most intense peaks at specific plane orientations, as shown in equation (2) [30]:

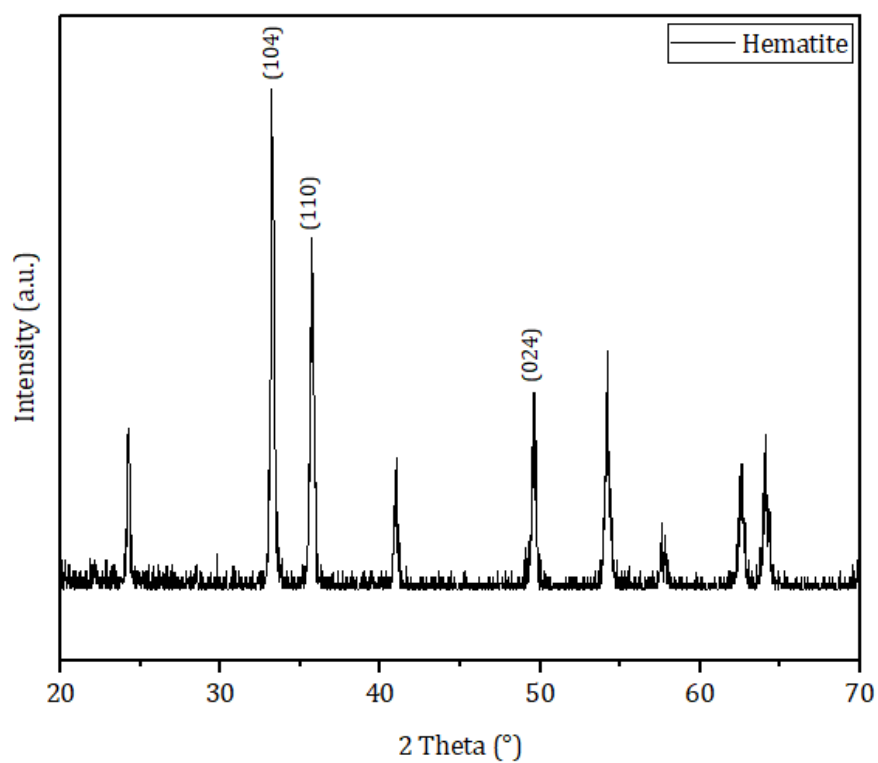
$$D = \frac{K\lambda}{\beta \cos\theta} \quad (2)$$

In this equation, λ represents the X-ray wavelength (1.5418Å), β denotes the full-width at the half maximum (FWHM) in radians, which correlates with broadening due to crystallite dimensions, θ is the Bragg diffraction angle, and K is the shape factor, typically taken as 0.9. The crystallite sizes calculated for ZnO, α -Fe₂O₃, and NiO are

summarized in Table 4. Figure 6 illustrates the XRD patterns for these samples, confirming their phase purity as indicated by the absence of any extraneous peaks [31].



(a)



(b)

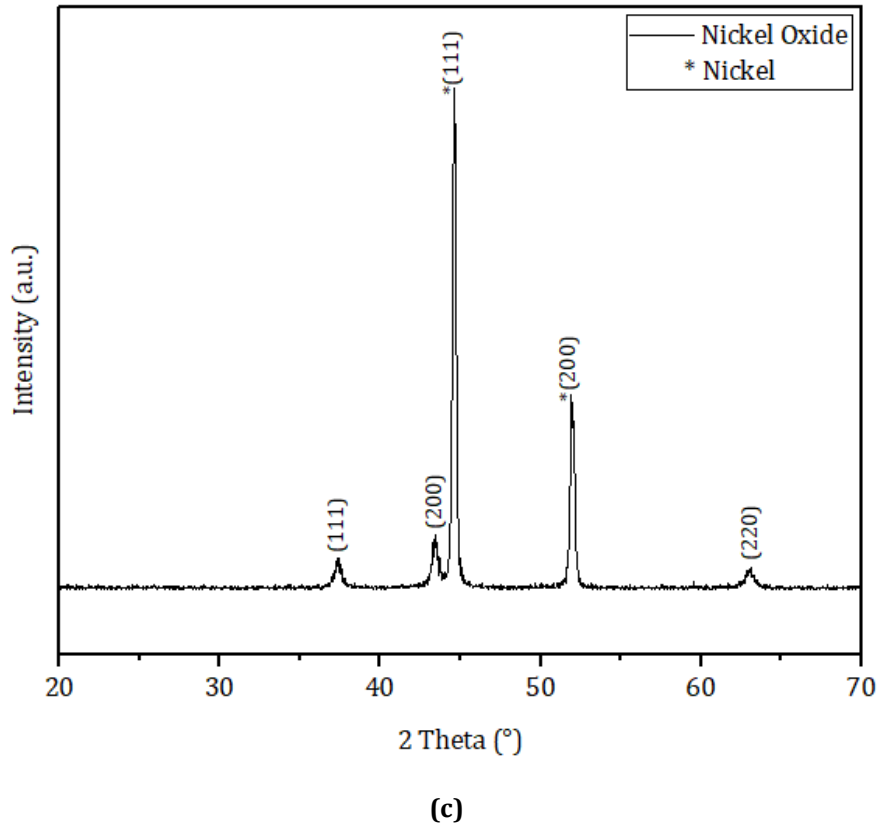


Fig. 6 (a) XRD of synthesized ZnO annealed at 500°C; (b) XRD of synthesized α -Fe₂O₃ annealed at 500°C; (c) XRD of synthesized NiO annealed at 500°C

For ZnO, primary diffraction peaks at 31.9° (100), 34.5° (002), and 36.3° (101) indicate a hexagonal wurtzite structure, with an average crystallite size of 35.7 nm. In α -Fe₂O₃, the prominent peaks at 33.3° (104), 35.7° (110), and 49.5° (024) are consistent with a trigonal phase, resulting in a mean crystallite size of 36.8 nm. Similarly, NiO exhibits cubic phase characteristics with notable peaks at 37.4° (111), 43.4° (200), and 63.1° (220), producing a smaller crystallite size of 18.2 nm.

The Debye-Scherrer calculation relies on the width of the XRD peaks, with narrower peaks generally indicating larger crystallites. The values in Table 4 support the high crystallinity and purity observed in these nanopowder samples.

Table 4 Crystallite size of ZnO, α -Fe₂O₃ and NiO calculated using Scherrer's formula at different planes

Sample	Crystallite size, D (nm)			Average (nm)
ZnO	(100)	(002)	(101)	35.7
	36.3	36.9	34.0	
	α -Fe ₂ O ₃	(104)	(110)	
36.9		32.3	41.3	36.8
NiO		(111)	(200)	
	17.8	23.2	13.7	

3.2 AC Breakdown Voltage Analysis

The variations in breakdown voltage among different NFs underscore the intricate relationship between nanoparticle type and concentration and their electrical performance, providing valuable insights for transformer applications. Similar research has been performed by [32]. Dielectric strength is a measure of an insulating material's ability to withstand electric stress without breaking down and is calculated by dividing the breakdown voltage by the distance between electrodes. The enhanced average breakdown voltages observed with ZnO and α -Fe₂O₃ nanoparticles suggest a significant improvement in dielectric strength.

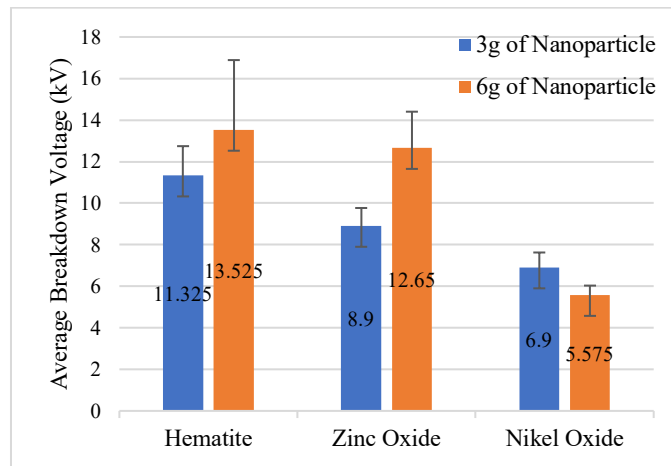


Fig. 7 Breakdown voltage of vegetable cooking oil with nanoparticles

Figure 8 illustrates the breakdown voltage for 3g of various nanoparticles mixed with vegetable cooking oil, each nanofluid having a concentration of 0.005g/ml. According to the line chart comparison, α -Fe₂O₃ nanoparticles exhibit the highest breakdown voltage at 12.1kV during the second cycle, followed by ZnO nanoparticles at 9.7kV in the first cycle. NiO nanoparticles display the lowest breakdown voltage at 7.7kV in the fourth cycle. The analysis of breakdown voltage results has been categorized into high and low concentrations to facilitate comparison within their respective groups.

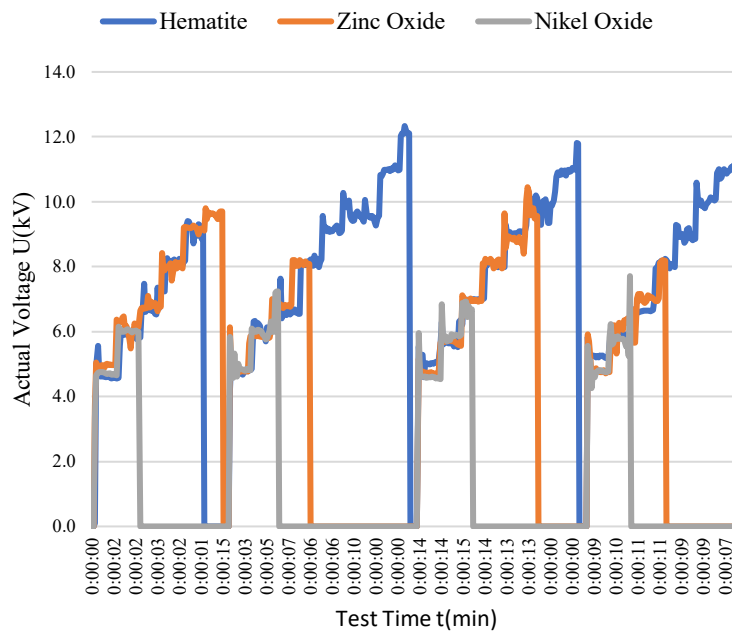


Fig. 8 Breakdown voltage of vegetable cooking oil with 3g different nanoparticles

Figure 9 shows the category of nanofluids containing 6g of nanoparticles. Within this group, the nanofluid with 6g of α -Fe₂O₃ exhibited a substantial improvement in average breakdown voltage compared to the base vegetable cooking oil without nanoparticles, which had a reference breakdown voltage of 9.025 kV. Across multiple cycles, the average breakdown voltage for the 6g α -Fe₂O₃ nanofluid ranged from 8.7 kV to 16.3 kV, with an overall average of 13.525 kV. This significant enhancement underscores the positive influence of α -Fe₂O₃ nanoparticles on augmenting the electrical insulation properties of vegetable cooking oil. In contrast, the nanofluids with 6g of ZnO displayed a more moderate trend in average breakdown voltage. Ranging from 11.2 kV to 15.2 kV across multiple cycles, the average breakdown voltage for the 6g ZnO nanofluid averaged 12.650 kV. While not as pronounced as the impact observed with α -Fe₂O₃, these results still indicate a notable improvement compared to the vegetable cooking oil without nanoparticles. In terms of percentage, the inclusion of α -Fe₂O₃

demonstrates a significant enhancement in AC-BDV, with an increase of 25.48% for 3g of $\alpha\text{-Fe}_2\text{O}_3$ and 49.86% for 6g of $\alpha\text{-Fe}_2\text{O}_3$ compared to the base oil value of 9.025 kV. Conversely, ZnO exhibits a noteworthy improvement in AC-BDV only at the 6g concentration, showing a percentage increase of 40.17%, while the lower concentration experiences a slight decrement of 1.39%. Lastly, NiO indicates a reduction in AC-BDV for both concentrations, with a decrease of 23.55% and 38.23%. In conclusion, $\alpha\text{-Fe}_2\text{O}_3$ proves to be the most effective nanoparticle for incorporation with vegetable cooking oil, showcasing a remarkable enhancement in AC breakdown voltage. Overall, the variations in average breakdown voltage among these nanofluids with 6g of nanoparticles highlight the nuanced effects of different nanoparticle types on the dielectric strength of the nanofluid. A study with comparable objectives was executed by [33]. These findings contribute valuable insights into potential applications, particularly in optimizing electrical performance in transformer operations

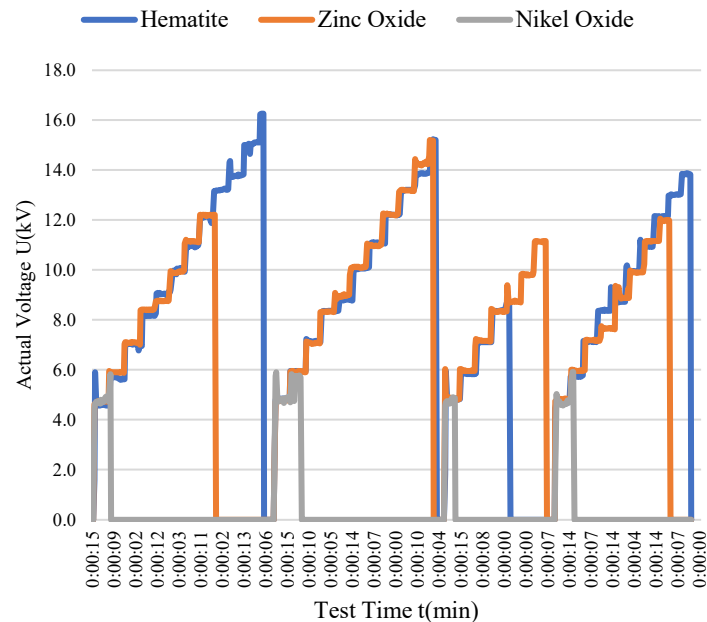


Fig. 9 Breakdown voltage of vegetable cooking oil with 6g different nanoparticles

4. Conclusion

This study provides a comprehensive examination of the breakdown voltage characteristics and structural analysis of seven nanofluid samples, leading to several pivotal conclusions. Firstly, Iron Oxide Hematite ($\alpha\text{-Fe}_2\text{O}_3$) consistently outperforms other nanoparticles in terms of breakdown voltage, regardless of concentration levels. Specifically, the integration of vegetable cooking oil with 3g and 6g of $\alpha\text{-Fe}_2\text{O}_3$ results in significant enhancements in AC-BDV, with improvements of 25.48% and 49.86%, respectively. In contrast, Nickel Oxide (NiO) consistently shows the lowest breakdown voltage for both low and high concentrations, highlighting its unsuitability as a liquid insulator in transformers. Furthermore, X-ray diffraction analysis reveals a direct correlation between nanoparticle purity, crystallinity, and resultant breakdown voltage. The well-defined diffraction peaks in the XRD pattern confirm the high purity and crystallinity of the synthesized Hematite ($\alpha\text{-Fe}_2\text{O}_3$) nanopowder, as explored by [34]. Additionally, the study underscores the critical influence of nanoparticle dispersion on breakdown voltage outcomes. All nanoparticles underwent a one-hour sonication process with vegetable cooking oil before testing, which proved effective for Hematite ($\alpha\text{-Fe}_2\text{O}_3$) and Zinc Oxide (ZnO) but not for Nickel Oxide (NiO), which displayed poor dispersion and a notable amount of precipitate. The surface chemistry of nanoparticles plays a pivotal role in their dispersion within a liquid medium, with $\alpha\text{-Fe}_2\text{O}_3$ and ZnO benefiting from surface properties that enhance their interaction with vegetable cooking oil, resulting in improved dispersion, as indicated by research performed by [35]. In summary, Iron Oxide Hematite ($\alpha\text{-Fe}_2\text{O}_3$) emerges as the superior nanoparticle compared to Zinc Oxide (ZnO) and Nickel Oxide (NiO). Hematite ($\alpha\text{-Fe}_2\text{O}_3$) not only demonstrates higher breakdown voltage but also exhibits a heightened level of purity and crystallinity, reinforcing its efficacy and stability in vegetable cooking oil. These findings contribute valuable insights into potential applications, particularly in optimizing electrical performance in transformer operations.

Acknowledgments

This research was not funded by any grant. The authors acknowledge the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA for the excellent facility provided for the research.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Nik Hakimi Nik Ali, Mohamad Hafiz Mamat; **data collection:** Norhafiz Azis; **analysis and interpretation of results:** Wan Muhammad Dzhahirul Bin Wan, A. S. Ismail, Norhafiz Azis; **draft manuscript preparation:** Wan Muhammad Dzhahirul Bin Wan, Fuad N. Alhabill. All authors reviewed the results and approved the final version of the manuscript.

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