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RESEARCH ARTICLE

Enhancement of AC Breakdown Voltage of Magneto Nanofluids Incorporating Co_3O_4 Nanoparticles

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ABSTRACT: Nanofluids have been adopted by power utilities to improve the dielectric capability of transformer oils. The demand for more compact power transformers has driven the need for insulating fluids with enhanced dielectric properties. This study examines the dielectric property of advanced magnetic nanofluids, formulated with synthetic ester oil and mineral oil, under various electric stress conditions. The Cobalt (II, III) oxide (Co_3O_4) nanoparticles were chosen due to the novelty of the Co_3O_4 nanomaterial and its better performance. Nanofluids were prepared using a two-step process, with concentrations of 0.005 wt.%, 0.010 wt.%, and 0.020 wt.% in base oil. The determination of breakdown voltage (BDV) was performed using a Verband Deutscher Elektrotechniker (VDE) and spherical-spherical (S-S) electrode system following the IEC 60156 standards. The maximum breakdown voltage is obtained at a particular concentration of nanoparticles for sphere and VDE electrodes. The 12 repetitions were carried out for each set of nanofluid, with BDV measurements noted. The results revealed a significant improvement in the BDV of the nanofluids. Each nanofluid demonstrated maximum % AC BDV enhancement at specific nanoparticle concentrations. The results indicate that the S-S electrode arrangement led to the highest overall improvement for Co_3O_4 in mineral oil, achieving a 16.10% enhancement, and for VDE electrode configuration led to the highest overall improvement for Co_3O_4 in synthetic ester oil, with an 18.76% enhancement.

Keywords: Synthetic Ester Oil, Magnetic Nanomaterial, Nanofluids, Dielectric Strength, AC Breakdown Enhancement.

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1. INTRODUCTION

Advancements in electric power systems have heightened the need for enhanced performance and consistency in numerous power system apparatuses. Among these, transformers are indisputably the most crucial, whether at the generation or transmission level. The steady rise in electrical power consumption, both industrially and domestically, has led to higher transformer ratings. Increasing a transformer's rating translates to a greater load, escalating the electrical and thermal stress on the transformer's windings and insulation structure. These combined factors place the transformer at a higher risk of failure, which can have severe consequences for the entire power system. Many transformers in use worldwide are nearing the end of their design lifespan, with some already exceeding it, making it crucial to focus on the consistency of these remaining units [1].

Statistics reveal that transformers that fail due to insulation problems have an average service life of 17.8 years, which is almost half of the anticipated lifespan of 35–40 years. For high-voltage transformers, approximately 75% of failures are attributed to insulation-related issues [2]. A transformer's operational reliability and lifespan largely depend on its insulation system. Transformer oil plays a key role in this system, making it essential to have a dependable insulating fluid to ensure the transformer operates smoothly. Mineral oil is transformers' most commonly used dielectric insulating fluid due to its outstanding dielectric properties and effective cooling capabilities [3-4]. However, due to the non-biodegradability and rapid depletion of oil reserves, it is essential to explore alternative oils [5-7]. In recent years, significant attention has been focused on alternative insulating oils, particularly natural ester oils. These oils,

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generally derived from vegetable sources, are extracted from crops and refined accordingly. Known as natural ester oils, they are named after their sources, such as sunflower oil, rapeseed oil, coconut oil, and palm oil [8-10]. In 1999, Waverly Light & Power in Iowa received another patent for a vegetable oil-based transformer liquid developed with soybean oil [11-12].

The key insulation medium for electric transformers characteristically consists of transformer oil (TO) insulation. Transformer insulating oil must remain stable at high temperatures to effectively suppress arcing, and perform the dual function of electric insulation and cooling. It acts as an electrical insulator between conductive components and helps dissipate heat generated during transformer operation [13]. Moreover, the transformer's weight, size, and current in winding are influenced by the quantity of oil used and heat transfer capabilities. The oil-immersed transformers experience various field stresses during operation, such as electrical, thermal, and chemical stresses, which accelerate the aging of the insulation system in transformers. The widespread use of oil/paper insulation systems in high-voltage apparatus has prompted significant research aimed at improving its dielectric properties [14]. Power transformers are reliable throughout their estimated life, and with proper maintenance, their lifespan can be extended to 60 years.

The combined effects of these factors speed up the degradation process of the oil/paper insulation, eventually leading to failure [15]. Therefore, finding an effective and economical way to enhance the breakdown performance of transformer insulation systems is crucial. The dielectric characteristics of synthetic ester oil are similar to those of mineral oils with some exceptions. Due to their biodegradability and fire resistance, natural ester oils are becoming a preferred alternative to conventional transformer oil [16].

Vegetable oils also have a lesser coefficient of expansion and can extend insulation life by 5–8 times than mineral oil. However, the higher viscosity of some vegetable oils results in a slower flow rate, leading to poorer thermal conduction. In high-temperature areas, transformers filled with synthetic ester oils and high ratings may require modifications to ensure adequate cooling for proper operation [17]. The dielectric characteristics of natural ester oil can be additionally improved by adding appropriate nanomaterials. Since the introduction of nanotechnology in the 1990s, nanofluids have gained significant attention due to advancements in the field [18].

Research has shown that dispersing nanomaterials like Fe_3O_4 [19], SiO_2 [20], and Al_2O_3 [21] in transformer insulating oil improves both dielectric strength and heat transfer capacity. Studies on these nanofluids have reported enhanced thermal and insulating properties, making it possible to increase transformer ratings and load handling capacity, which in turn boosts the overall productivity and consistency of electrical power systems.

With advances in nanotechnology, a novel fluid called NF has been developed to enhance device conductivity. Nanofluids are created by combining a base fluid with low thermal conductivity with solid nanoparticles (NPs) that have high thermal conductivity, resulting in a new fluid with superior heat transfer properties compared to traditional base liquids. A nanofluid (NF) consists of nanometer-sized particles evenly dispersed in the base fluid, forming a colloidal solution [24]. The nanoparticles used in nanofluids are typically made from metals (such as gold, copper, aluminum, and iron), oxides (like TiO2, SiO2, CuO, and Al2O3), nonmetals (including carbon nanotubes, graphene, and graphite), metal nitrides (such as SiN, AlN), and metal carbides (like SiC). The base fluids commonly include oil, water, and ethylene glycol Figure 1. Nanofluids exhibit unique characteristics that make them potentially suitable for various heat transfer applications, including microelectronics, vehicle thermal management, heat exchangers, refrigerator chillers, and temperature reduction in boiler flue gases [25].

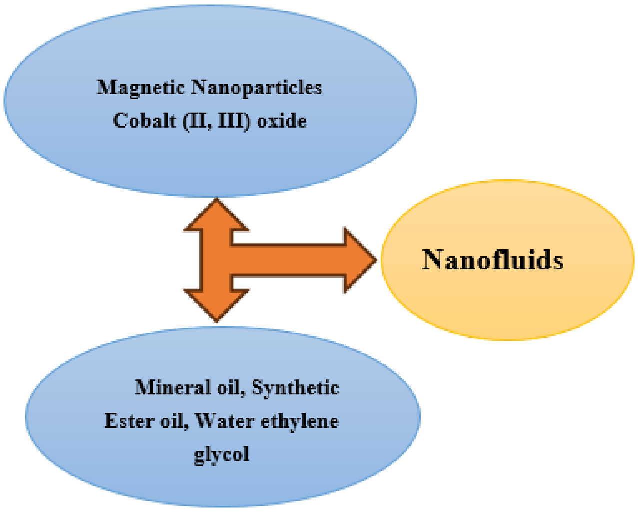

Fig. 1. Schematic illustration to prepare nanofluids.

Unfortunately, the current insulation systems in use have limited electrical and thermal performance, leading to a significant need to address thermal, electrical, mechanical, and economic challenges. For instance, suspending micron-sized particles in traditional liquid insulation could create a thermally efficient system by combining the properties of both the solid particles and the base liquid. However, while this approach enhances thermal properties, such as thermal conductivity, it also introduces additional flaws in the overall insulation system.

Nanofluids (NFs) are expected to demonstrate unique dielectric properties that differ significantly from those of traditional micro-fluids. The notable improvement in these properties, attributed to the presence of nanoparticles, has resulted in the emergence of a new category of fluids offering both electrical and thermal benefits. Consequently, numerous research efforts have been undertaken to investigate the potential of NFs as next-generation liquid insulation for AC and DC power transmission systems.

In recent decades, nanofluids (NFs) have garnered significant attention due to their exceptional and unique properties. Although a few review articles have explored the dielectric properties of NFs, it appears that none have focused on their thermal characteristics. This article not only provides insights into the thermal properties of transformer oil-based NFs nevertheless also offers a comprehensive overview of the related challenges and future opportunities. Additionally, it summarizes the advantages, disadvantages, and possible applications of these NFs. The pros and cons associated with nanoparticles (NPs) and NFs are illustrated in Figure 2.

In this work, mineral and synthetic ester oil are the base fluids for dispersing nanoparticles. Synthetic ester oils have a higher viscosity associated with mineral oil [22]. The study focuses on a specific type of nanomaterial, Co_3O_4, which is semi-conductive and also exhibits magnetic properties. Co_3O_4, as a bulk material, is a p-type semiconductor with antiferromagnetic properties. The research aims to examine the effects of this nanomaterial on the mineral oil and synthetic ester oil blend, and to conduct a relative analysis of the improved properties of the resulting insulating nanofluid [23].

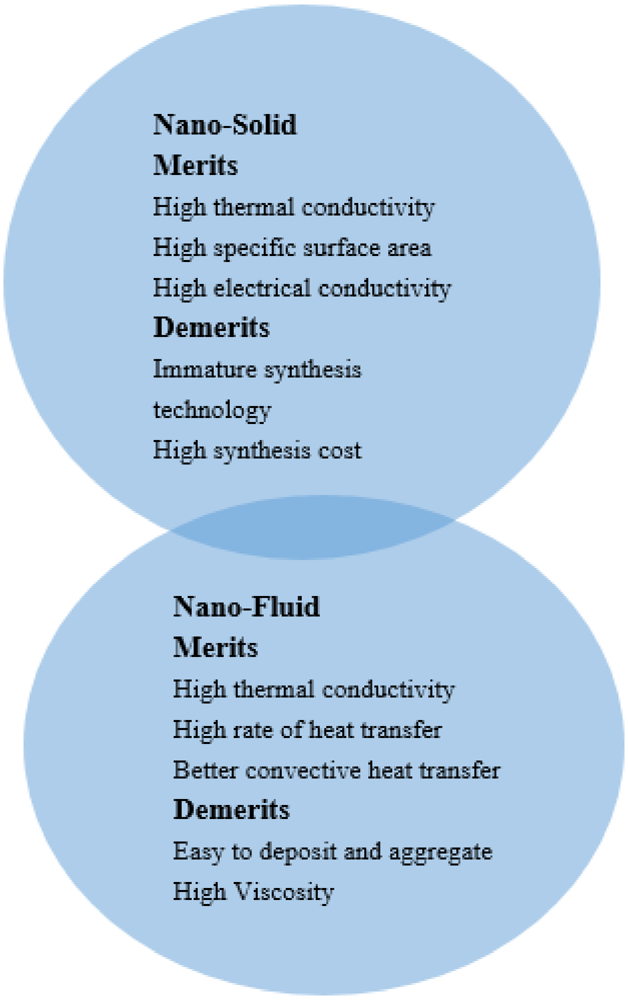

Fig. 2. A summary for the merits and demerits of nano-solids (nanomaterials), and nanofluids.

2. EXPERIMENTAL DETAILS

2.1. Selection of Nanoparticles and Oils

For this study, cobalt oxide nanoparticles (Co_3O_4) were selected due to their favorable electrical and thermal properties. The nanoparticles were synthesized using a ball milling apparatus at the Interdisciplinary Nanotechnology Centre (INC), Aligarh Muslim University (AMU), employing a top-down nanotechnology approach. This method is well-suited for producing nanoscale materials with precise control over particle size and morphology. The specific characteristics of the synthesized nanoparticles, including their size, shape, and crystallinity, are summarized in Table 1.

Previous studies have primarily relied on traditional mineral oils for dielectric fluid research. However, this study focused on modern, biodegradable insulating oils currently used in commercial applications. The oils included both mineral and synthetic ester-based insulating oils. These oils were chosen for their environmentally friendly properties and high dielectric performance. Their detailed physical and chemical properties are listed in Table 2.

2.2. Preparation of Nanofluids

The preparation of oil-based nanofluids involves two primary methods: the one-step and two-step approaches. While the one-step method is suitable for low-viscosity fluids, it often results in limited dispersion stability. For this experiment, the two-step method was adopted due to its superior dispersion stability, as depicted in Figure 3.

2.3. Materials and Procedure

The nanofluids were prepared using Co_3O_4 nanoparticles and the selected insulating oil. Initially, the nanoparticles were weighed according to the required concentrations: 0.005 wt.%, 0.010 wt.%, and 0.020 wt.%. The nanoparticles and oil were placed in a beaker, and a magnetic stirrer was used for preliminary mixing. A magnetic stirrer is a laboratory device that employs a rotating magnetic field to spin a stir bar ("flea") placed inside the liquid, effectively stirring the solution. The stirring process was carried out for approximately 30 minutes to ensure a homogeneous mixture.

2.4. Sonication Process

After initial stirring, the dispersion of nanoparticles was further enhanced using an ultrasonic bath. Sonication is a widely used technique in nanotechnology for dispersing nanoparticles in liquids and breaking apart aggregated particles. This process ensures a uniform distribution of nanoparticles throughout the insulating oil, preventing sedimentation.

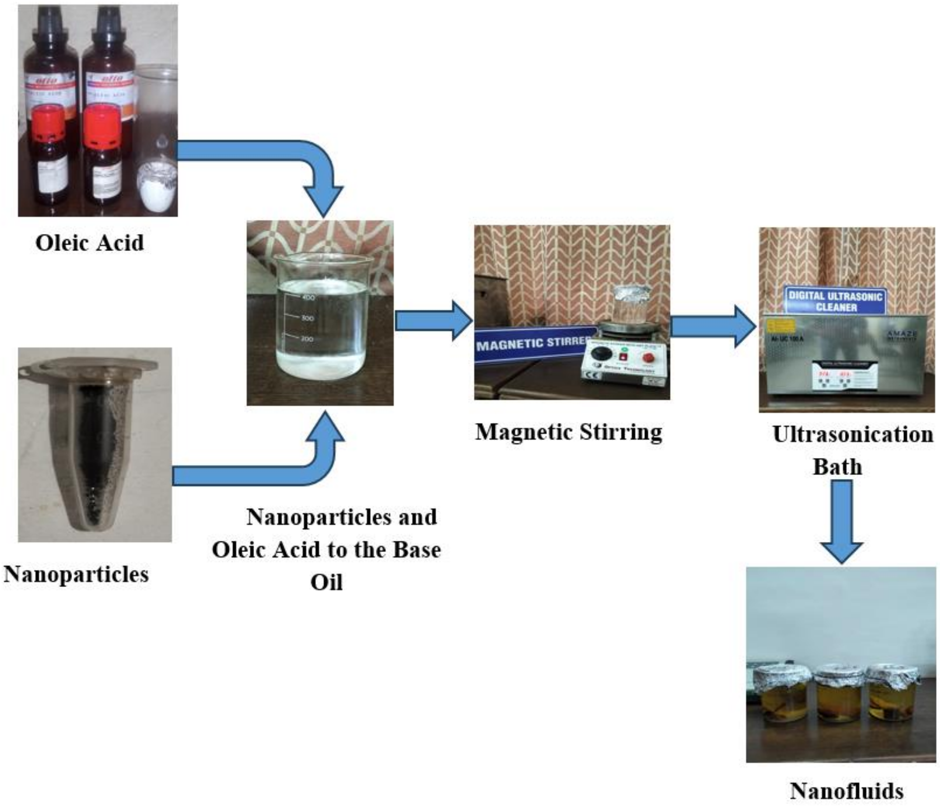

Fig. 3. Schematic diagram showing the preparation of nanofluids.

Table 2. Properties of Mineral Oil and Synthetic Ester Oil.

Composition	Mineral oil	Synthetic ester oil
Freezing point	− 12.2 °C	−60 °C
Boiling range	305-605°C	330-370°C
Flash point	125-140°C	325-335°C
Relative density	0.90 at 20 °C	0.97 at 20 °C
Water solubility	< 1 mg/l	< 1 mg/l
Viscosity	20 mm^2/s at 40 °C	29 mm^2/s at 40 °C
Explosive property	Non-explosive	Non-explosive
Color	Dark brown	light orange

The sonication was performed for three hours at a controlled temperature to avoid thermal degradation of the insulating oil. After sonication, the prepared nanofluids were securely covered and left undisturbed for 24 hours to ensure stability and protect the mixture from moisture contamination. Moisture in insulating oil can significantly degrade its dielectric properties, especially the breakdown strength.

2.5. AC Breakdown Voltage (BDV) Measurement

To evaluate the dielectric performance of the nanofluids (NFs), the AC dielectric breakdown voltage (AC BDV) was measured, as transformers primarily operate on AC voltage. The breakdown voltage test was conducted using an oil breakdown tester in accordance with IEC 60156 standards.

Table 1. Properties of Co_3O_4 Nanoparticles.

Properties	Co_3O_4 Nanoparticles
Density (20°C)	6.07g/cm^3
Molar Mass(20°C)	240.80 g/mol
Melting Point	895 °C
Boiling Point	900 °C
Particle Size	70-110 nm
Appearance	Particle

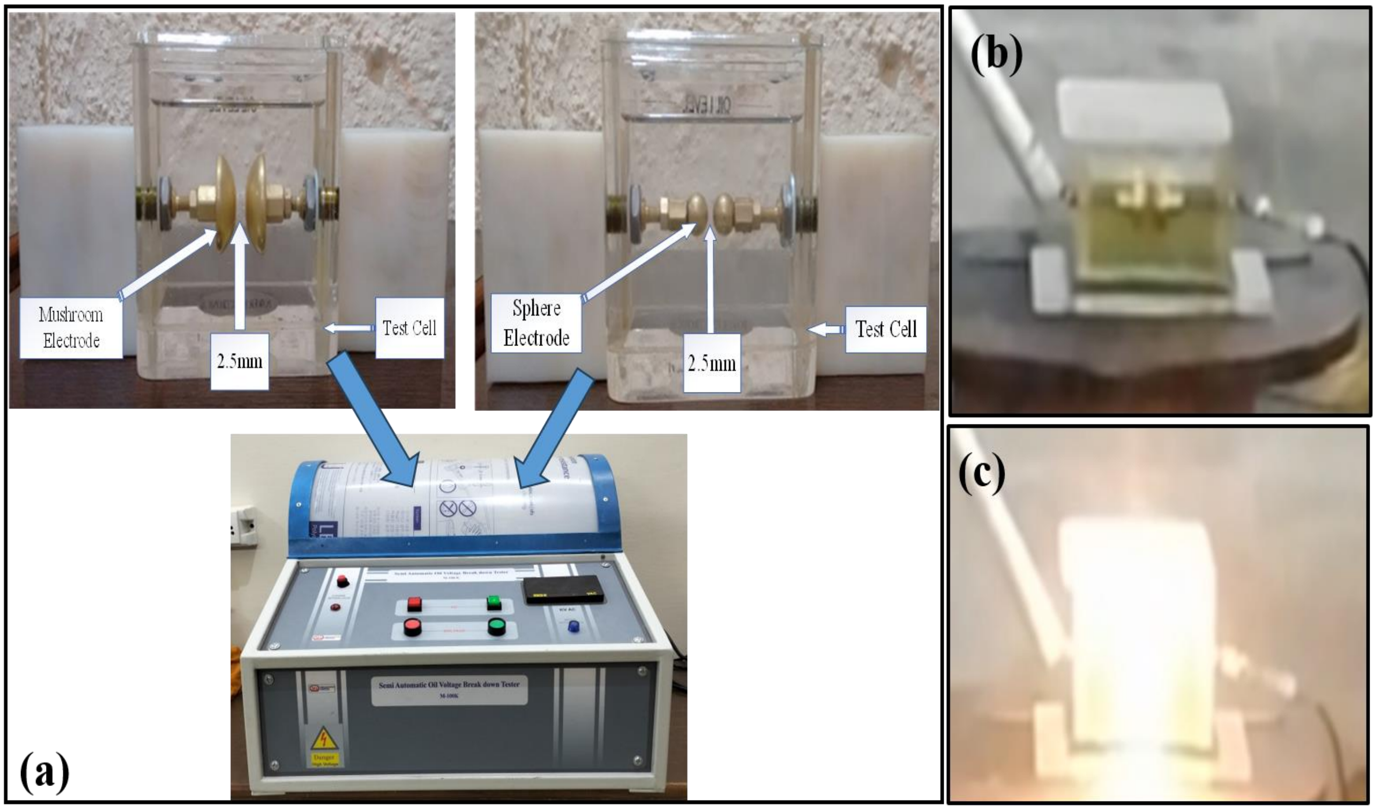

Fig. 4. Automatic AC BDV tester for measuring AC BDV of dielectric liquid: (a) VDE electrode configuration and Sphere-Sphere electrode configuration; (b) before dielectric breakdown; (c) during dielectric break.

The setup included specific electrode configurations, as shown in Figure 4(a). Two types of electrodes were employed: *Verband Deutscher Elektrotechniker (VDE) Electrode:* Conforming to standardized geometry for consistent testing. *Spherical Electrode:* Used to simulate varying stress conditions.

The electrode gap was carefully adjusted to ensure uniform electric stress distribution during testing. The oil-filled vessel was allowed to settle for 5 minutes prior to testing to eliminate visible air bubbles. The test voltage, with a frequency ranging between 48 Hz and 62 Hz, was applied using a step-up transformer. The voltage was increased linearly from zero at a rate of 2.0 $kVs^{-1} \pm 0.2\ kVs^{-1}$ until dielectric breakdown occurred, marked by the formation of an arc and a short circuit. The breakdown event was visually confirmed through the appearance of a flashover or spark, as illustrated in Figure 4(b) and 4(c).

To ensure accurate measurements, a minimum interval of two minutes was maintained between successive tests, allowing residual gas bubbles to dissipate. Additionally, the electrodes were carefully inspected and cleaned to ensure no nanoparticle residue remained after each breakdown test. Multiple tests were conducted for each nanofluid sample to establish reliable averages for the breakdown voltage. The enhancement in AC BDV was assessed by comparing the mean AC BDV of the nanofluid samples (AC BDVmean_{nf}) to that of the corresponding base oils (AC BDV mean_base_oil). The percentage improvement in AC BDV was calculated using the following formula:

$$\Delta \text{AC BDV}\ (\%) = \left(\frac{AC\ \ BDV\ \ mean_{nf}}{AC\ \ BDV\ \ mean_{base_{oil}}} - 1 \right) \times 100$$

This analysis provided insights into the electrical performance enhancement of the insulating oils with increasing nanoparticle concentrations.

3. RESULTS AND DISCUSSION

3.1. AC Breakdown Strength

The dielectric breakdown test serves as a crucial evaluation method to assess the electrical performance of insulating oils, particularly for transformers. In this study, the AC Breakdown Voltage (AC BDV) test was carried out using a fully automated oil breakdown tester that included an enclosed chamber for oil samples and specific electrode configurations. Following the ASTM D877 standard, the brass electrodes were arranged with a fixed gap of 2.5 mm and a diameter of 10 mm. The rate of voltage rise was maintained at 2 kV/sec, and all measurements were performed at room temperature to ensure consistency and relevance to real-world operating conditions [24, 25].

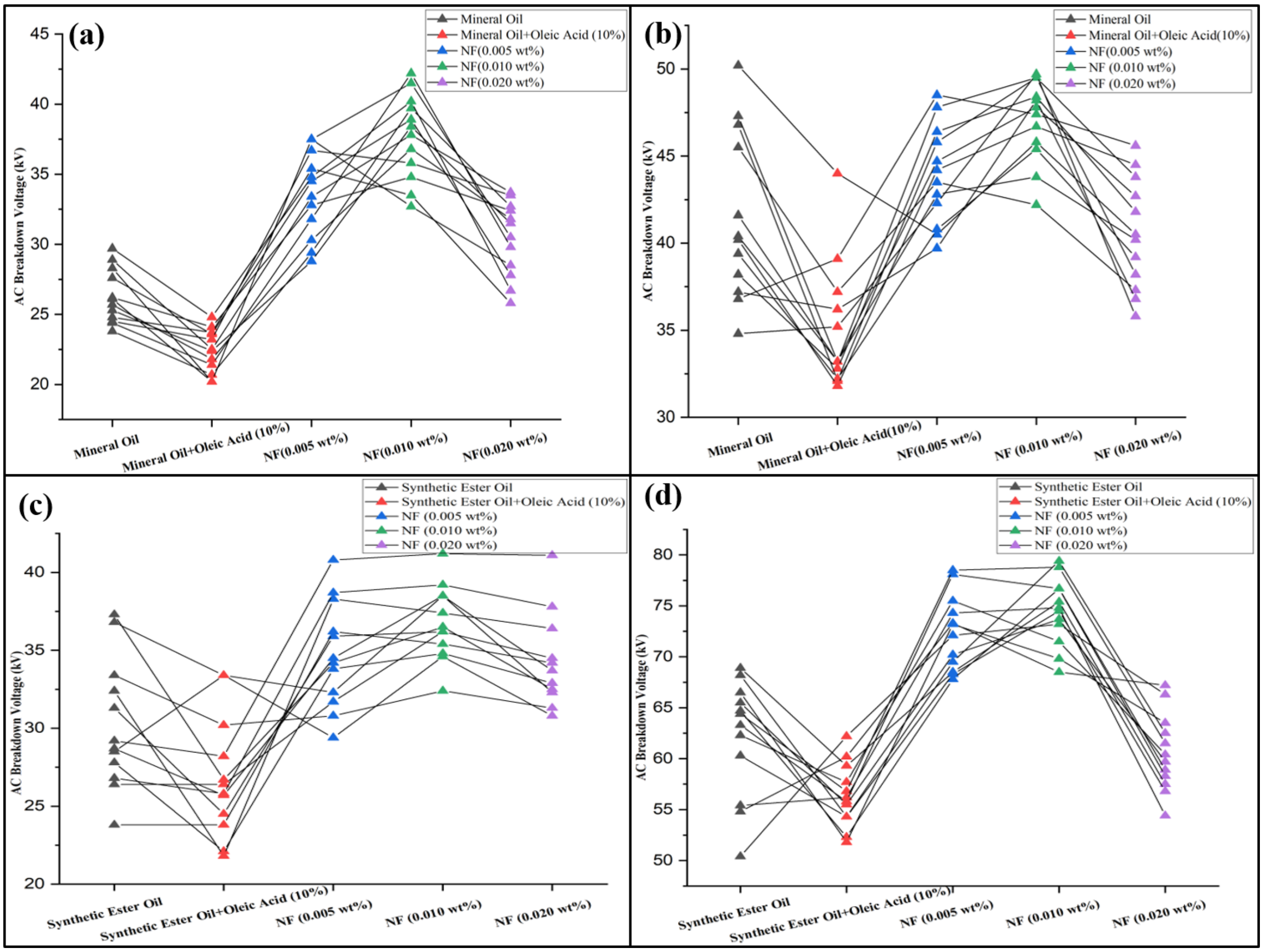

Fig. 5. The AC breakdown voltage of (a) mineral oil and related nanofluids including Co_3O_4 nanoparticles under the S-S electrode arrangement, (b) mineral oil and related nanofluids under the VDE electrode arrangement, (c) synthetic ester oil and related nanofluids including Co_3O_4 nanoparticles under the S-S electrode arrangement, and (d) synthetic ester oil and related nanofluids under the VDE electrode arrangement.

3.2. Experimental Setup and Procedure

The oil breakdown tester was equipped with two distinct electrode configurations, namely sphere-sphere (S-S) and mushroom-mushroom (M-M), to simulate different stress conditions and replicate actual transformer applications. These configurations were in compliance with the ASTM D-1816 standard, which is widely accepted for assessing breakdown properties in insulating materials. The nanofluid was poured into a sealed chamber up to the designated oil level marking and then subjected to voltage until breakdown occurred. For each nanofluid sample, 12 breakdown voltage (BDV) readings were recorded to account for statistical variability. The final AC BDV for each sample was calculated as the average of these readings. To ensure the reliability and reproducibility of results, the test was conducted twice for each oil sample in separate batches. This rigorous approach minimized experimental errors and ensured consistency across all measurements [26]. Figures 5(a) and 5(b) illustrate the breakdown voltage results for mineral oil and its related nanofluids under the S-S and VDE (Verband Deutscher Elektrotechniker) electrode arrangements, respectively. Similarly, Figures 5(c) and 5(d) display the corresponding results for synthetic ester oil and its related nanofluids under the same electrode configurations.

3.3. Influence of Nanoparticle Concentration on AC BDV

The results clearly demonstrate that the addition of Co_3O_4 nanoparticles significantly influences the AC BDV of both mineral oil and synthetic ester oil. At lower nanoparticle concentrations, the AC BDV increased steadily, reaching a peak at an optimal concentration. Beyond this point, however, a decline in AC BDV was observed, which can be attributed to the agglomeration of nanoparticles [27].

3.4. Breakdown Mechanism

At optimal concentrations, the nanoparticles act as charge-trapping sites, enhancing the oil's ability to withstand higher electrical stresses before breakdown. This improvement can be explained by the electron scavenging capability of Co_3O_4 nanoparticles, which reduces the mobility of free electrons in the oil. The nanoparticles effectively suppress the propagation of conductive channels, thereby delaying the onset of breakdown. However, at higher concentrations, the nanoparticles begin to cluster, forming chain-like agglomerates. These agglomerates create conductive pathways within the oil, which serve as weak points for electrical discharge. Consequently, the breakdown voltage decreases. This phenomenon highlights the importance of determining the optimal nanoparticle concentration for each insulating oil to maximize its dielectric performance.

3.5. Impact of Humidity and Stability

Another factor influencing the observed decline in AC BDV at higher nanoparticle concentrations is the accidental introduction of humidity during sample preparation. Moisture in the insulating oil can significantly degrade its dielectric strength by reducing the oil's ability to resist electrical discharge. Proper sample preparation protocols, including the use of ultrasonic dispersion and sealed containers, are critical to minimizing such issues. Additionally, the stability of the nanofluids plays a pivotal role in determining their electrical performance. While magnetic stirring and sonication were employed to ensure uniform dispersion of nanoparticles, prolonged stability tests may be required to confirm the long-term homogeneity of the nanofluids.

3.6. Comparative Analysis of Mineral Oil and Synthetic Ester Oil

The comparative analysis of mineral oil and synthetic ester oil reveals distinct trends in their AC BDV performance. Mineral oil demonstrated a higher initial BDV, which can be attributed to its superior dielectric properties. However, synthetic ester oil exhibited a greater enhancement in BDV upon the addition of nanoparticles, likely due to its inherent compatibility with nanomaterials and better dispersion stability. For instance, under the S-S electrode configuration, the peak AC BDV for mineral oil-based nanofluids was achieved at a nanoparticle concentration of 0.01 wt.%, while synthetic ester oil-based nanofluids reached their peak at a slightly higher concentration of 0.015 wt.%. This difference suggests that the interaction between nanoparticles and the base oil matrix plays a significant role in determining the optimal concentration.

3.7. Electrode Configuration and Breakdown Strength

The choice of electrode configuration also influenced the AC BDV results. The S-S configuration, characterized by a uniform electric field distribution, produced higher BDV values compared to the M-M configuration, which introduces localized field intensities. This finding underscores the importance of electrode geometry in evaluating the dielectric properties of insulating oils and their nanofluids.

The findings of this study have significant implications for the development of advanced insulating materials for transformers. By optimizing the concentration of Co_3O_4 nanoparticles, it is possible to enhance the dielectric performance of both mineral and synthetic ester oils. This improvement can lead to higher operational reliability and efficiency in transformers, particularly under high-voltage conditions. Moreover, the use of biodegradable synthetic ester oils combined with nanoparticles represents a sustainable alternative to traditional mineral oils. These eco-friendly nanofluids not only offer improved electrical performance but also align with the growing demand for environmentally responsible transformer technologies. Despite the promising results, this study has certain limitations that warrant further investigation. First, the long-term stability of the nanofluids needs to be thoroughly evaluated under varying temperature and humidity conditions. Second, the impact of different nanoparticle materials and shapes on the dielectric properties of insulating oils should be explored to identify the most effective combinations. Future research could also focus on understanding the molecular-level interactions between nanoparticles and oil molecules to gain deeper insights into the mechanisms governing dielectric enhancement. Advanced characterization techniques, such as Raman spectroscopy and molecular dynamics simulations, could be employed to elucidate these interactions. Additionally, the scalability of nanofluid production and its economic feasibility for industrial applications should be assessed. While the two-step preparation method used in this study is effective for laboratory-scale experiments, alternative methods may be required for large-scale manufacturing. This study highlights the potential of Co_3O_4 nanoparticles as an additive to enhance the dielectric performance of transformer-insulating oils. The results demonstrate that the optimal nanoparticle concentration is a critical factor in maximizing the AC BDV of nanofluids. Both mineral oil and synthetic ester oil exhibited significant improvements in breakdown strength upon the addition of nanoparticles, with synthetic ester oil showing greater enhancement due to its compatibility with nanomaterials. The findings emphasize the importance of careful sample preparation, stability testing, and electrode configuration in evaluating the electrical properties of nanofluids. By addressing the limitations and exploring new research directions, it is possible to further advance the development of high-performance, eco-friendly insulating materials for transformers.

4. CONCLUSION

The dielectric properties of insulating oils play a pivotal role in the performance and reliability of power transformers. This study demonstrated that magnetic nanofluids, incorporating Co_3O_4 nanoparticles, exhibit superior breakdown voltages compared to pure mineral and synthetic ester oils. This enhancement can be attributed to the high dielectric permittivity of magnetic nanoparticles, which effectively improve electrical properties by reducing leakage currents, minimizing the formation of hotspots, and enhancing overall breakdown resistance. Additionally, these nanoparticles contribute to a more uniform electric field distribution, reducing the occurrence of localized breakdowns and increasing the dielectric strength of the oil. The magnetic nanoparticles also play a critical role in inhibiting charge carrier movement within the oil, thereby preventing the formation of conductive paths that could compromise the oil's insulating capabilities. Experimental results revealed that the AC breakdown voltage (AC BDV) is influenced by the type of electrode configuration. Notably, the VDE electrode configuration exhibited higher breakdown voltages compared to the S-S electrode configuration across various nanoparticle concentrations. In terms of specific improvements, the S-S electrode arrangement resulted in the highest enhancement for Co_3O_4 nanoparticles in mineral oil, achieving a 16.10% increase in breakdown voltage. Similarly, the VDE electrode configuration yielded the most significant enhancement for Co_3O_4 nanoparticles in synthetic ester oil, achieving an 18.76% improvement. These findings underline the potential of nanofluid technology as a promising avenue for enhancing the dielectric performance of transformer oils, providing a pathway for the development of more efficient and reliable electrical insulation systems in power transformers. Future research should focus on optimizing nanoparticle concentrations and exploring the impact of different nanoparticle types and oil formulations to further enhance dielectric properties.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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REFERENCES

[1] Tsovilis, T., Peppas, G., Staikos, E., Hadjicostas, A. and Datsios, Z., **2024.** Exploring the surge current degradation of natural ester oil-based nanofluids. *Scientific Reports*, *14*(1), p.7584.

[2] Sudhakar, T., Muniraj, R., Jarin, T. and Sumathi, S., **2024.** Nanofluid-enhanced vegetable oil blends: a sustainable approach to breakthroughs in dielectric liquid insulation for electrical systems. *Biomass Conversion and Biorefinery*, pp.1-24.

[3] Wang, Q., Rafiq, M., Lv, Y., Li, C. and Yi, K., **2016.** Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil. *Journal of Nanotechnology*, *2016*(1), p.5802753.

[4] Rafiq, M., Shafique, M., Ateeq, M., Zink, M. and Targitay, D., **2024.** Natural esters as sustainable alternating dielectric liquids for transformer insulation system: analyzing the state of the art. *Clean Technologies and Environmental Policy*, *26*(3), pp.623-659.

[5] Rao, U.M., Fofana, I., Beroual, A., Rozga, P., Pompili, M., Calcara, L. and Rapp, K.J., **2020.** A review on pre-breakdown phenomena in ester fluids: Prepared by the

international study group of IEEE DEIS liquid dielectrics technical committee. *IEEE Transactions on Dielectrics and Electrical Insulation*, *27*(5), pp.1546-1560.

[6] Nadimuthu, L.P.R., Moorthy, N.S., Victor, K., Thenkaraimuthu, M., Khan, B. and Ali, A., **2024.** An experimental and spectroscopic investigation on pongamia pinata as liquid dielectrics for rural micro grid under various load conditions. *Scientific reports*, *14*(1), p.19653.

[7] Yang, H., Chen, S. and Ding, J., **2024**. Design of a Transformer Oil Viscosity, Density, and Dielectric Constant Simultaneous Measurement System Based on a Quartz Tuning Fork. *Sensors*, *24*(9), p.2722.

[8] Prasad, R., Sreekanth, C., Muniraj, R. and Jarin, T., **2024.** Characterization and aging impact study on antioxidants with CaO catalyzed methyl ester from waste cooking oil as sustainable insulation as biorefinery approach. *Biomass Conversion and Biorefinery*, pp.1-18.

[9] Jiang, Z., Li, X., Zhang, H., Zhang, E., Liu, C., Fan, X. and Liu, J., **2024.** Research Progress and Prospect of Condition Assessment Techniques for Oil–Paper Insulation Used in Power Systems: A Review. *Energies*, *17*(9), p.2089.

[10] Xiang, C., Zhou, Q., Li, J., Huang, Q., Song, H. and Zhang, Z., **2016.** Comparison of dissolved gases in mineral and vegetable insulating oils under typical electrical and thermal faults. *Energies*, *9*(5), p.312.

[11] Farade, R.A., Wahab, N.I.A., Mansour, D.E.A. and Soudagar, M.E.M**., 2023.** The Effect of Nanoadditives in Natural Ester Dielectric Liquids: A Comprehensive Review on Stability and Thermal Properties. *IEEE Transactions on Dielectrics and Electrical Insulation*, *30*(4), pp.1478-1492.

[12] Baruah, N., Nayak, S.K. and Pratihar, S.K., **2021.** Quantitative effect of aging duration on dielectric parameters based on frequency response. *IEEE Transactions on Instrumentation and Measurement*, *71*, pp.1-9.

[13] Swamynathan, K., Sthalasayanam, N., Sridevi, M. and Sudheesh, A.K., **2024.** Novel Method Using Transformer Moisture Equilibrium for Removal of Absorbed Moisture from Cellulose Paper Insulation in Power Transformers. *Journal of The Institution of Engineers (India): Series B*, pp.1-11.

[14] Spro, O.C., Mauseth, F. and Peftitsis, D., **2021.** High-voltage insulation design of coreless, planar PCB transformers for multi-MHz power supplies. *IEEE Transactions on Power Electronics*, *36*(8), pp.8658-8671.

[15] Jiang, T., Deng, B., He, Q., Bi, M., Chen, X., Bao, L. and Zhou, X., **2023.** The Study on Weibull Failure Models for Oil Gap–Paper Insulation Under Pulsating DC Voltage with Temperature. *Journal of Electrical Engineering & Technology*, *18*(2), pp.805-814.

[16] Rafiq, M., Shafique, M., Azam, A. and Ateeq, M., **2021.** Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation-A review. *Ain Shams Engineering Journal*, *12*(1), pp.555-576.

[17] Bhunia, M.M., Panigrahi, K., Naskar, C.B., Bhattacharjee, S., Chattopadhyay, K.K. and Chattopadhyay, P., **2021.** 2D square nanosheets of Anatase TiO2: A surfactant free nanofiller for transformer oil nanofluids. *Journal of Molecular Liquids*, *325*, p.115000.

[18] Rafiq, M., Chengrong, L. and Lv, Y., **2019.** Effect of Al_2O_3 nanorods on dielectric strength of aged transformer oil/paper insulation system. *Journal of Molecular Liquids*, *284*, pp.700-708.

[19] Tian, W., Tang, C., Wang, Q., Zhang, S. and Yang, Y., **2018.** The effect and associate mechanism of nano SiO_2 particles on the diffusion behavior of water in insulating oil. *Materials*, *11*(12), p.2373.

[20] Khaled, U. and Beroual, A., **2018.** AC dielectric strength of mineral oil-based Fe_3O_4 and Al_2O_3 nanofluids. *Energies*, *11*(12), p.3505.

[21] Pourpasha, H., Zeinali Heris, S., Javadpour, R., Mohammadpourfard, M. and Li, Y., **2024**. Experimental investigation of zinc ferrite/insulation oil nanofluid natural convection heat transfer, AC dielectric breakdown voltage, and thermophysical properties. *Scientific Reports*, *14*(1), p.20721.

[22] Nazari, M., Jafarmadar, S. and Gohery, S., **2023.** Convective heat transfer behavior and AC dielectric breakdown voltage of electric power transformer oil with magnetic colloidal nano-fluid: An experimental study. *Case Studies in Thermal Engineering*, *45*, p.103017.

[23] Rizwan, M., Khan, S.A., Khan, M.R. and Khan, A.A., **2024.** Experimental and statistical investigation on the dielectric breakdown of magneto nanofluids for power applications. *Journal of Materials Science: Materials in Engineering*, *19*(1), p.5.

[24] Khan, S.A., Tariq, M., Khan, A.A., Urooj, S. and Mihet-Popa, L., **2022.** An experimental study and statistical analysis on the electrical properties of synthetic ester-based nanofluids. *Energies*, *15*(23), p.9127.

[25] Shafique, M. and Luo, X., **2019.** Nanotechnology in transportation vehicles: An overview of its applications, environmental, health and safety concerns. *Materials*, *12*(15), p.2493.

[26] Oparanti, S.O., Fofana, I., Jafari, R. and Zarrougui, R., **2024**. A state-of-the-art review on green nanofluids for transformer insulation. *Journal of Molecular Liquids*, p.124023.

[27] Zhang, E., Liu, J., Zhang, C., Zheng, P., Nakanishi, Y. and Wu, T., **2023.** State-of-art review on chemical indicators for monitoring the aging status of oil-immersed transformer paper insulation. *Energies*, *16*(3), p.1396.